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Wood-based biochemical innovation systems: challenges and opportunities

Master's thesis

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Tiivistelmä – Referat – Abstract

The structural changes concerning the forest industry sector will stimulate the incumbents in the sector to develop new product areas for the replacement of the old, declining core products. Wood-based biochemicals are considered as one of the major product areas able to compensate the decline in revenues caused by diminishing demand for graphic papers. There is already existing demand for biochemicals from the owners of major product brands who seek to replace fossil-based raw materials with more sustainable alternatives. New wood-based product areas respond to the changing operating environment of the sector but also require new types of business models and strategies as well as development of expertise from different fields.

This work examines the systemic weaknesses and strengths of the development of the Finnish wood-based biochemical sector as well as the policy tools facilitating the development and diffusion of the sector. This study was carried out as a qualitative study where literature review was complemented with eight semi-structured expert interviews. The conceptual basis for analyzing the material were based on innovation theories, enabling the identification of the weaknesses and strengths of the system.

The results revealed several drivers for the further progression of the system but specifically two internal functions of the system were identified which can be recognized to hinder the optimal development of the entire system. The development and diffusion of knowledge as well as the differing expectations and visions between system actors were identified as barriers to the further development of the system, necessitating more effective policy measures.

As this study addressed specifically the systemic weaknesses and strengths, it would be important for the future studies to address more detailed policy measures in order to enhance the further promotion of the sector. This approach should also consider the relationship of the wood-based biochemicals as a part of the whole biochemical sector and its development.

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wood-based biochemicals, innovation systems, biorefineries, system weaknesses, system strengths

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Innovaatiosysteemit puupohjaisiin biokemikaaleihin liittyen: haasteet ja mahdollisuudet

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Tiivistelmä – Referat – Abstract

Metsäteollisuuden toimialaan kohdistuvat rakenteelliset muutokset edistävät sektorin toimijoiden insentiivejä kehittää uusia tuotealueita taantuvien ydintuotteiden tilalle. Puupohjaisia biokemikaaleja pidetään yhtenä merkittävänä tuoteavauksena, joka voi osaltaan kompensoida graafisten paperien kysynnän heikentymisen aiheuttamaa liikevaihdon laskua. Biokemikaalien kohdalla on jo havaittavissa kysyntää esimerkiksi merkittävien tuotebrändien omistajilta, jotka pyrkivät korvaamaan fossiilisia raaka-ainepohjia kestävämmillä vaihtoehdoilla. Uudet puupohjaiset tuotealueet vastaavat muuttuvaan sektorin toimintaympäristöön, mutta vaativat myös uudenlaisia liiketoimintamalleja ja -strategioita sekä uuden osaamisen kehittämistä.

Tämä työ tarkastelee suomalaisen puupohjaisten biokemikaalien sektorin kehittymiseen liittyviä systeemisiä heikkouksia ja vahvuuksia sekä niitä politiikkakeinoja, joilla olisi mahdollista edistää tämän sektorin kehittymistä sekä diffuusiota. Tutkimus toteutettiin laadullisena tutkimuksena, jossa kirjallisuuskatsausta täydennettiin kahdeksalla puolistrukturoidulla asiantuntijahaastattelulla. Materiaalin analysointiin hyödynnettiin innovaatiotutkimuksen menetelmiä, jotka mahdollistivat systeemiin kohdistuvien heikkouksien ja vahvuuksien identifioinnin.

Tuloksista ilmeni useita ajureita, jotka tukevat systeemin jatkuvaa kehittymistä, mutta erityisesti kaksi systeemin sisäistä funktiota identifioitiin, joiden puutteellisen kehittymisen voidaan nähdä heikentävän koko systeemin optimaalista kehittymistä. Tiedon kehittäminen ja leviäminen toimialan osapuolten välillä sekä toisaalta systeemin toimijoiden väliset odotukset ja visiot pystyttiin identifioimaan systeemin kehityksen esteeksi, joiden helpottamiseksi tulisi muodostaa nykyisiä politiikkakeinoja tehokkaampia menettelytapoja.

Tämä tutkimuksen käsitellessä ensisijaisesti sektorin systeemisiä heikkouksia ja vahvuuksia olisi tärkeää jatkaa spesifimpien politiikkakeinojen tunnistamista tulevissa tutkimuksissa koko sektorin kehityksen edistämiseksi. Tässä menettelyssä tulee ottaa myös huomioon ennen kaikkea puupohjaiset biokemikaalit osana koko biokemikaalisektoria ja sen kehitystä.

Avainsanat – Nyckelord – Keywords

puupohjaiset biokemikaalit, innovaatiotutkimus, biojalostamot, systeemiset heikkoudet, systeemiset vahvuudet

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Contents

1. Introduction

The structural changes affecting the forest industry sector bring simultaneously new opportunities through novel outputs while on the other hand, the mature, declining core products are affected by the change in the product portfolios. As Näyhä (2019) states, the new trends driving the change in societies and markets, including changing consumer demands and values, globalization, digitalization, climate change, resource scarcity and increasing sustainability awareness combined with transition towards bio- and circular economies transforms the competitive markets into a more complex entity, demanding innovative approaches from the incumbent industry actors. New emerging product areas derived from wood biomass respond to the changing business environment but additionally require also nontraditional business strategies and models as well as expertise from different fields, necessitating progressive cross-sectorial collaboration (Toppinen et al., 2017).

Biochemicals are identified as one of the most prominent new markets for emerging wood-based products that can compensate the declined revenues from graphical papers as a result of undergoing structural changes in the global markets (Hurmekoski et al., 2018). Biochemical sector has already shifted from technology push led by major chemical companies to market pull created by leading consumer brands such as P&G, IKEA, LEGO, and the Coca Cola Company, which have set specific targets on replacing fossil-based chemicals with more sustainable alternatives (Biddy et al., 2016).

According to Jönsson et al. (2012), in order to achieve the potential for an increased use of biomass in biochemicals, petrochemical cluster should make a transition towards biorefinery cluster, basing their business on renewable feedstock and energy. As switching to biogenic feedstock demands extensive amounts of biomass, wood-based solutions could provide a more sustainable basis for raw material compared to 1st generation feedstocks (Murat et al., 2016). Moreover, the development of the biorefinery concept, integrated into the pulp and paper industry, remains vital for the realization of the new opportunities and business diversification within the forest cluster (Hämäläinen et al., 2011). As Rafione et al. (2014) notify, by obtaining building block chemicals from the biorefining process, the raw material which would normally be burnt to recover its energy content can be used for the production of high value-added bioproducts, promoting the most efficient use of the feedstock.

Several wood-based biochemicals are acknowledged to entail potential for commercialization. For instance, ethanol, furfural, lactic acid and succinic acid could be seen as new chemical opportunities from biorefinery carbohydrates (Bozell and Petersen 2010) while multiple lignin derivatives have been introduced as complementary platforms for fossil alternatives (e.g. Dessbesell, Pulkki, and Leitch (2017)). One example of an already existing commercialized pathway for biochemicals utilizing forestry feedstock is the crude tall oil-based pine chemicals industry. As a by-product from the Kraft pulping process (Adewale and Christopher, 2017), crude tall oil illustrates resource efficiency through its cascading use of biomass. This pattern of ensuring economic and social value of the biomass by maximizing it through product processing and upgrading along the downstream value chain constitutes the delineation for the entire forest biochemical sector.

In a broader perspective, the national as well as supranational strategies of promoting bio-based economy and alternatives for fossil-based products are also required in order to succeed in the transition process. As Staffas, Gustavsson, and Mccormick (2013) state, many countries have published separate strategies and policies for biotechnology and bio-based products. Imbert et al. (2017) point out that the promotion of bioeconomy is dependent on different policy efforts across a wide spectrum of policy spheres. Seizing the opportunities regarding the innovation and technological change while mitigating the potential risks will have a strong dependency on the employed policies and regulations throughout the transition process. Hence, establishing policy mixes for the promotion of innovation in emerging technology fields forms a salient feature for the future policy strategies.

Innovation can take a form of a new and significantly improved product, process, marketing method or a business practice. Markard and Truffer (2008) point out that innovation processes typically depend on the co-development of new socio-technical configurations, new market structures, new actors and new institutional settings. Conceptually, innovation systems can be defined at different levels for different purposes of analysis. According to

Edquist (2009a), they are composed of networks including actors and institutions developing, diffusing and using innovations. Innovation systems can be compared and evaluated by the system functions in order to derive policy recommendations (Bergek et al., 2005).

1.1 Aim of the study

According to Kleinschmit et al. (2014), the majority of bioeconomy studies describe natural sciences and engineering perspectives, e.g. biotechnology or genetic engineering, thus giving less attention to the economic and policy challenges that are materially involved in the process. As innovations are needed in developing new, greener businesses, gaining deeper understanding on the market and policy forces interacting and shaping the conditions for biochemicals is required. Hence, this study concentrates on the forces impacting the interphase of forest-industry and chemical industry as well as what kind of drivers support or hinder the development of wood-based chemical innovations.

Furthermore, while the traditional industrial boundaries continue blurring, uncertainty remains regarding how different types of firms will position themselves along the renewing value-chains. Relying on the innovation system approach presented by Markard and Truffer (2008) and multilevel framework by Geels (2002), this study aims to understand the wood-based chemical innovation system development focusing on the following research questions:

1. What are the components of the innovation system of the forest-based biochemicals sector in Finland?
2. What are the system weaknesses and strengths of the forest-based biochemicals sector development in Finland?
3. What could be the key policies to enhance the further development and diffusion of innovations in the biochemical sector?

The structure of the thesis is as follows. The concepts regarding biochemicals and illustrations of exemplary wood-based biochemical cases are presented in the second section while applied theories are presented in the section 3. Section 4 addresses the research methods, data collection and data analysis while in section 5, the results of the study are presented. Section 6 includes the discussion related to the research results and the recommended policy variables while section 7 contains the conclusions from the study. Addedly, the appendix includes the questionnaire used for data collection (in English and Finnish).

2. Background

Although the biochemical concept generates growing interest among the different stakeholders, the production of bio-based chemicals is not a novelty. Still, as de Jong et al. (2012) state, fossil-based feedstocks, primarily oil and gas, represent the main crude material for the majority of organic chemicals and polymers. The global petrochemicals production of chemicals and polymers is estimated to be around 360 million tonnes (Table 1) and the primary output is dominated by a few key building blocks, namely ethylene, propylene, butadiene, benzene, toluene, xylene and methanol (Pohjakallio, 2015). The main applications for these building blocks are polymers and plastics but they can also be converted into a vast number of various specialty and fine chemicals.

Table 1. Base chemicals and their estimated annual production volumes. Source: Adapted from Pohjakallio (2015).

Base chemical	Main raw material	Global annual production from main raw materials (tonnes)	Global annual production from bio-based raw materials (tonnes)
Ethylene	Oil, gas	123 300 000	200 000
Propylene	Oil, gas	74 900 000	pilot scale
Butadiene	Oil, gas	10 200 000	pilot scale
Benzene	Oil	40 200 000	>100
Toluene	Oil	19 800 000	>100
Xylene	Oil	42 500 000	>100
Methanol	Syngas	49 100 000	340 000

According to de Jong et al. (2012), technically close to all fossil-based industrial materials could be made from bio-based resources. Excluding biofuels, the global bio-based chemical and polymer production is estimated to be around 50 million tonnes with products such as non-food starch, cellulose fibres and cellulose derivatives, tall oils, fatty acids and fermentation products. Furthermore, Pohjakallio (2015) notifies that wood biomass is compatible raw material for almost all present fossil-based chemicals. The bioeconomy is evolving rapidly and many new solutions and processes are being developed in the chemical sector. The market for bio-based chemical products in Europe is expected to grow at an annual rate of around 5% and reach a level of 40 billion euros in 2020.

However, according to Hurmekoski et al. (2018), rather than competing primarily with petrochemicals, wood-based chemicals are seen to face competition principally from the other biochemicals made with first- and second-generation feedstocks, resulting in moderately low volume estimates. Furthermore, Carus et al. (2016) point out several factors potentially hindering the development of wood-based chemicals. The high priced C5 and C6 sugars for fermentation processes from lignocellulosic biorefineries distinctly exceeds the prices of the first-generation feedstocks. A potential solution to the cost disadvantage would require the utilization of lignin but as Mccormick (2018) states, many of the marketed end uses for lignin remain still at the development phase, taking at least 5-10 years to mature.

In addition, the determination of bio-based content varies between different actors, hence generating a need for clear communication about the characteristics of the bio-based products. As Willemse and van der Zee (2018) state, the term bio-based only stands for the product's wholly or partially derived biomass content, thus leaving other product characteristics such as LCA performance, biodegradability or sustainability of biomass used unnoticed.

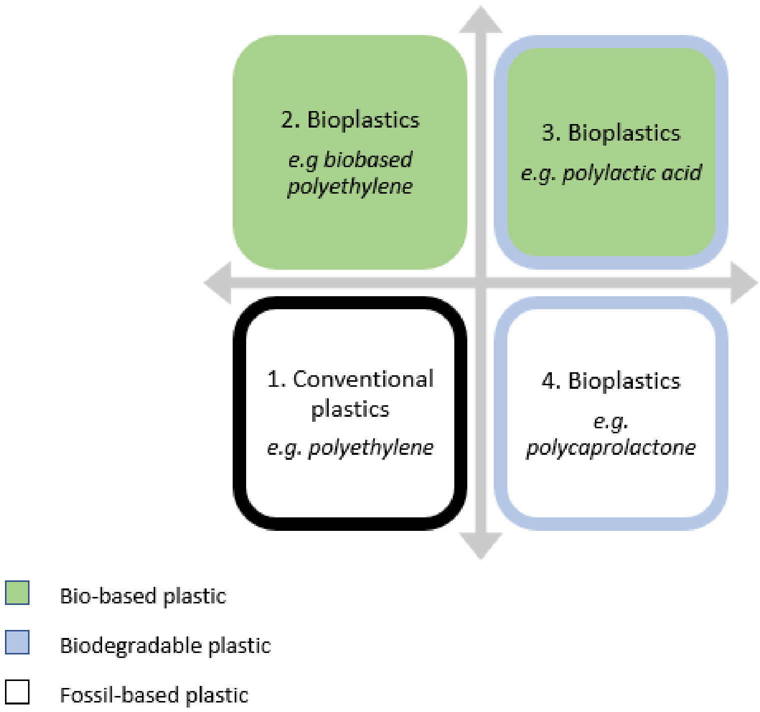

Fig. 1. Illustration of different properties between conventional plastics and bioplastics. Source: Adapted from Mccormick (2018).

For instance, Mccormick (2018) states that bioplastics are often misunderstood as a synonym for biodegradable plastics even though biodegradable plastics can be produced also from 100% fossil materials (Fig. 1.) Therefore, it remains important that these characteristics are being assessed and communicated separately.

According to Willemse and van der Zee (2018), European Union (EU) approach to the determination of bio-based content differs between bio-based content and bio-based carbon content. EU bio-based carbon content refers to the amount of bio-based organic and inorganic carbon in proportion to the total amount of carbon in sample while EU bio-based content refers to the amount of bio-based carbon, hydrogen, nitrogen and oxygen in proportion to the total mass of the sample. In addition, U.S. bio-based content refers to the amount of bio-based organic carbon in proportion to the total amount of organic carbon in the sample. de Guzman (2015) notifies that this versatility with definitions will cause businesses such as recycling industries to refuse bio-based products as they are afraid that bio-based products will undermine the quality of their recycling stream. Hence, it is crucial for businesses to recognize these differences and clearly state which standards are being used to avoid confusion in the market place.

2.1 Definition of the forest-based biochemical value chain

The proposed value chain of producing forest-based biochemicals is based on general industry practice (personal communication, Stora Enso executive, January 2018). It consists of different production phases as showed in Fig. 2.

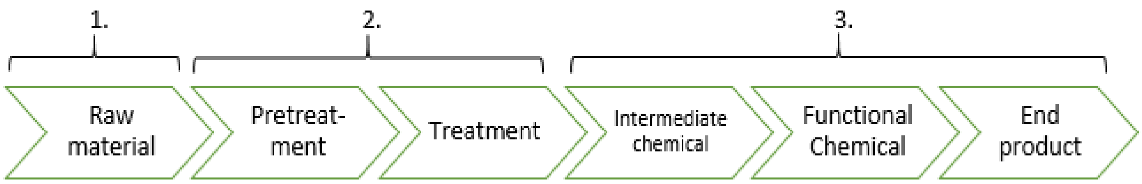

Fig. 2. Proposed value chain for the bio-based chemicals production.

The value chain can be divided into three sections in the same manner as in Wang (2015):

1. Upstream
2. Midstream
3. Downstream

Upstream comprises of events related to raw material resources including biomass management, harvesting and first stage logistics. Midstream refers to the production of the platform chemical. This phase consists of the technical processes of conversing biomass into the desired biochemical, logistics and sales of the product. Downstream includes functions from the further processing of the biochemicals to the final applications of the different products (Wang, 2015).

The targeted markets for the proposed value chains depend considerably on the chemical in demand. The structure for the classification of different bio-based chemicals can be made according to Carus et al. (2017). This approach divides biochemicals into three different classes: drop-in, smart drop-in and dedicated chemicals (Fig. 3.). Bio-based drop-in chemicals such as bio-based methane or bio-based propylene are substitutes for existing petrochemicals which have established markets and are chemically identical to the fossil-based chemicals in question. These commodity chemicals are easy to implement technically with their compatibility regarding the existing infrastructure. However, even though the bio-based drop-in chemicals form a more sustainable alternative compared to their fossil counterparts, the more costly productions routes lead commonly to competitive issues (Carus et al., 2017).

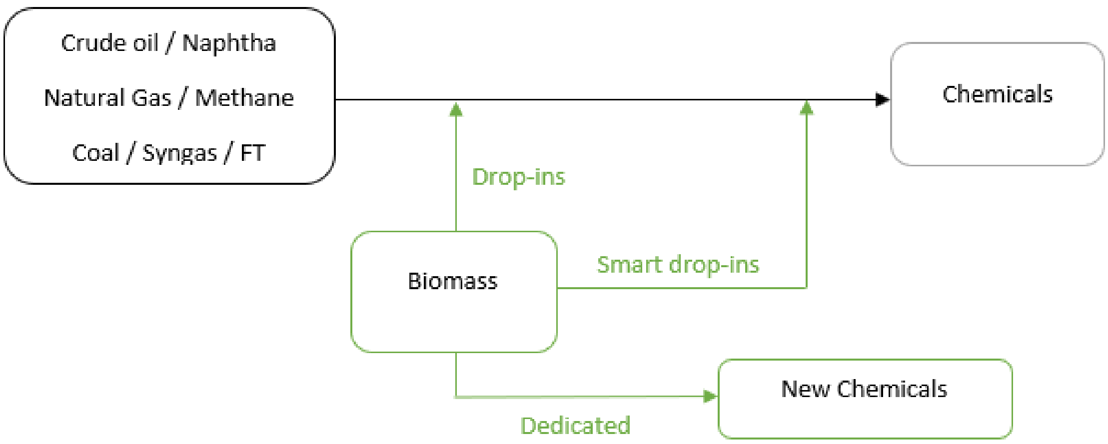

Fig. 3. Pathways for different bio-based chemicals. Source: Adapted from Carus et al. (2017).

Smart drop-in chemicals are also identical to the fossil hydrocarbons-based chemicals. The difference lies in their bio-based pathways as they provide advantages compared to the conventional pathways. Suggested standards for drop-in chemicals to be smart drop-ins are if at least two of the following criteria app (Carus et al., 2017):

- The Biomass Utilization Efficiency (Iffland et al., 2015) from feedstock to product is significantly higher compared to other drop-ins, referring to improved land use efficiency.
- Their production requires significantly less energy compared to other production alternatives.
- Time-to product is shorter due to shorter and less complex production pathways compared to the fossil-based counterpart or other drop-ins.
- Less toxic or harsh chemicals are used or occur as by-products during their production process compared to the fossil-based counterpart or other drop-ins.

Examples for bio-based smart drop-ins can be epichlorohydrin or succinic acid.

Dedicated bio-based chemicals have a dedicated pathway and are short of identical fossil-based counterparts. These chemicals could therefore offer unique and superior properties that fossil-based alternatives are lacking (BIO-TIC, 2014). Different examples of dedicated biochemicals are lactic acid, furfural and even cellulose fibres including nano- and microcellulose (Carus et al., 2017).

There are three different value chains of interest from the perspective of this study. These value chains differentiate with their technology readiness level (Fig. 4.) which determines their schedule for the possible commercialization (Horizon 2020, 2015). The first value chain is based on Crude Tall Oil. The second value chain is based on xylose production as feedstock for further refining. The proposed dedicated biochemical downstream process will lead to the production of D/L-lactic acid and ultimately to manufacturing of polylactic acid. The third value chain is based on lignin-derived products as base chemicals.

1	2	3	4	5	6	7	8	9
Basic research	Technology formulation	Applied research	Small scale prototype	Large scale prototype	Prototype system	Demonstration system	Completed commercial system	Full commercial application

Fig. 4. Illustration of technological readiness levels (TRL). Source: Adapted from (Horizon 2020, 2015).

2.2 Biorefineries

International Energy Agency (IEA) Bioenergy Task 42 defines biorefinery as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)"(de Jong et al., 2012). By using this definition, there are four main features to classify and describe a biorefinery system (de Jong et al., 2012):

1. Platforms (e.g. core intermediates such as C5-C6 carbohydrates, syngas, lignin, pyrolytic liquid)
2. Products (e.g. energy carriers, chemicals and material products)
3. Feedstock (i.e. biomass, from dedicated production or residues from forestry, agriculture, aquaculture and other industry and domestic sources)
4. Processes (e.g. thermochemical, chemical, biochemical and mechanical processes)

According to de Jong et al. (2012), the most important feature in this classification are the platforms as they are key intermediaries between raw materials and final products. Platforms can also be used to link different biorefinery concepts and target markets.

Another common way to divide biorefineries is to categorize them into three different generations. This practice is based on their primary feedstock material, processing flexibilities and products (Naik et al., 2010). According to Moncada, Tamayo, and Cardona (2014), the first generation biorefineries use crops as feedstock, the second generation uses residues, agroindustrial residues and non-edible crops and the third generation is based on algae. Especially first generation biorefineries use feedstock that competes directly with food and feed crops. Moving to second and third generation biorefineries enables feedstock usage that does not create additional demand for land use change, hence this is in line with the European Union policy of reducing indirect land use change (ILUC). However, cost-effective technologies required to more advanced commercially scaled biorefinery production are still on development. Sirajunnisa and Surendhiran (2016) state that second generation feedstocks have not been utilized for commercialization of the products due to these reasons. Regardless, second generation cellulosic ethanol can be more effective and promising as an alternative fuel due to its great net greenhouse gas emission reductions as well as higher net fossil fuel displacement potential (Huang et al., 2008).

The transition to a bio-based economy has several interlinked drivers that also approbate the development of biorefineries. These drivers include the global issue of climate change and the need to reduce greenhouse gases, an over dependency on fossil fuel imports, the sustainability of oil, gas, coal and phosphorus production in the long term and countries need to diversify their energy sources as well as the need to stimulate regional and rural development. However, the main driver in the short run for the development of biorefinery processes is the transportation sector including the heavy duty road transport and aviation sector leading to rapid expansion in biofuel production (de Jong et al. 2012, King 2010). There is a problem with the high production costs regarding biofuel production with the current oil prices, thus leading to approaches such as co-production of both value-added products (chemicals, materials, food, feed) and biofuels in order to derive value from all of the products maximizing biorefineries' overall economics. In some cases, value-added products could even be the primary revenue stream (de Jong et al. 2012, Naik et al. 2010).

In the context of this study, the main interest is on second generation lignosellulosic feedstock biorefineries (LCF) that can be based on lignosellulosic biomass from wood. Sirajunnisa and Surendhiran (2016) notify that trees contain high amount of carbohydrates and wood biomass is more significant renewable resource than other biomasses in Nordic area. Moreover, wood biomass does not compete with the food supply, thus promoting European Union policy objectives.

From the resource point of view according to Antikainen et al. (2017), the existing and novel products of biorefineries using forest-based feedstock are based on two main chemical pulping processes: kraft and sulphite pulping. These processes differentiate from each other with the ways of utilizing the raw material component. Sulphite mills are more versatile when it comes to product range (for example, sulphite mills are using lignin and hemicelluloses to create commercial products whereas kraft mills have not concentrated so much on these components). Historically this has been in order to compensate for less efficient energy recovery and inferior fibre quality of the sulphite mills. This has turned into a form of advantage as the growing interest in biorefineries has arised. The low price of kraft pulp and increasing competition from low labor cost countries has also led the kraft pulp mills to diversify their product offering in order to improve their competitiveness (Aro and Fatehi, 2017).

As the existing pulp mills could be the foundation for forest biorefineries, this concept is valuable effort to increase the overall revenue streams and profitability of the pulp mills by producing biofuel and chemicals (Huang et al., 2008). In the case of biofuels, de Jong et al. (2012) state that a variety of different biorefinery configurations are being developed but the necessary economic return is still largely dependent on policy assists and subsidies. This means that forest based biorefinery needs to generate sufficient value from its entire product range such as pulp, biofuel, energy and chemical production to increase the economic viability for biofuel production.

An exemplary illustration of the possible production routes for forest biorefineries can be presented as in the Fig. 5. (Huang et al., 2008). The integrated forest biorefinery aims to utilize all feedstock components producing several value-added co-products along with the major products. Huang et al. (2008) suggest following processes:

- Pre-extraction of hemicellulosic sugars (H) prior to pulping;
- Isolation of long and short fiber (C) after pulping;
- Hemicellulose conversion to ethanol in a bioreactor;
- Short fiber cellulose conversion to ethanol in another bioreactor;
- Long fiber cellulose conversion to fiber-based materials;
- Production of syngas from lignin (L) dissolved into black liquor.

The processes and process technologies will vary depending on the desired end products, hence the process block diagram in Fig. 5. presents only a mere example of the possible solutions when considering the potential forest-based biorefinery solutions. The key objective for a biorefinery is the optimization of resource usage and waste minimization, leading to benefit and profitability maximization (King 2010).

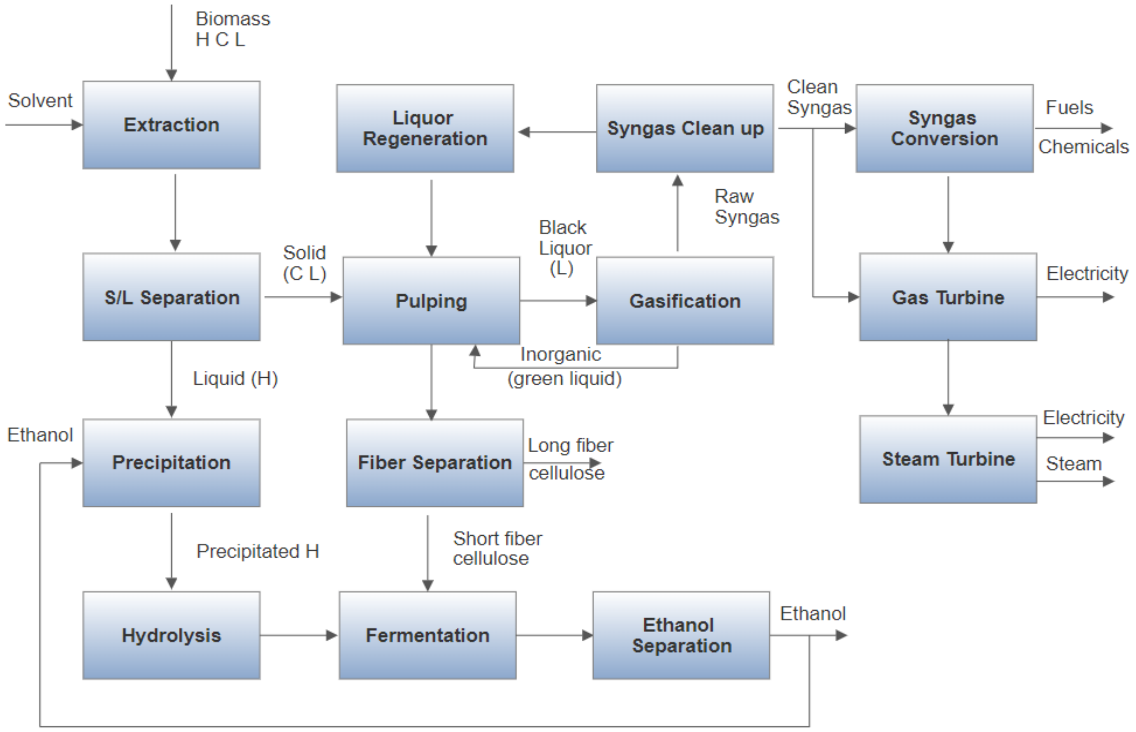

Fig. 5. Process block diagram of a forest biorefinery. Source: Adapted from Huang et al. (2008).

Biofuels and biochemicals comprise the essential core for new forest biomass product categories, thus making them highly interesting to analyze. As Bozell and Petersen (2010) point out, these product categories differentiate when considering the two processes. Research in fuels investigates several different technologies to produce a single or very small number of pre-identified outputs. This focus on product identification leads to the choice of technology. On the contrary, bio-based chemical production uses broad-based technologies to produce multiple outputs, thus focus on the choice of technology results in product identification. Hence, this basis could be a complicating factor for the incorporation of chemical products into the biorefinery's product portfolio.

2.2.1 Case: Äänekoski biorefinery

The bioproduct mill by Metsä Fibre in Äänekoski, Finland represents an interesting opportunity to explore the different operations of a second generation biorefinery. According to Metsä Fibre (2018), the bioproduct mill is creating a diverse ecosystem of bioeconomy companies manufacturing their products around the mill and converting side streams of the pulp production into value-added bioproducts. This objective was a central principle in the design of the mill and the gradual expansion of the product offering into completely new manufactures while striving for closed chemical cycle drives the transition of full valorization of lignocellulosic biomass.

The product range of the biorefinery from main and side streams includes 1) traditional bioproducts, 2) new bioproducts that have already been agreed upon and 3) some new concepts under development. Traditional products are pulp, tall oil and turpentine and the generation of bioenergy. New bioproducts include product gas from bark to be used as biofuel for the mill, sulphuric acid from odorous gases for the mill, biogas and biopellets from sludge to be used as fuel in transport and industry and biocomposites from pulp. New concepts involve new biofuels from surplus bark, fertilizers and earthwork materials from dregs and ash, new bioproducts from lignin and new textile fibres from pulp (Metsä Group, 2018).

The bioproducts manufactured from the side streams of the process account for 20 per cent of the mill's sale and the share continues its gradual growth. Although the efficient pulp mill forms the core of the whole biorefinery complex, the network of companies around the mill continues to expand. This network using both pulp and process side streams includes Metsä Board, CP Kelco, Äänevoima, Specialty Minerals and EcoEnergy SF. Moreover, Metsä Group and Itochu established a joint venture, Metsä Spring, to build an industrial demo plant for the production of wood-based textile fibres. The network of companies supports the competitiveness of the biorefinery complex while also increases the supply for new types of wood-based bioproducts (Metsä Group, 2018).

As Kamm and Kamm (2004) mention, the development of industrial biorefinery technologies and biobased products requires both introduction and establishment of biorefinery demonstration plants as well as commitment from chemistry for the concept of bio-based products and biorefinery systems. With the example set up by the Metsä Fibre's bioproduct mill, the adaptation of the biorefinery concept and the ecosystem platform could increase further, simultaneously expanding the potential manufacturing of wood-based biochemicals.

2.3 Biochemical examples

This section provides insights into three different biochemical applications that either are already solid business cases or have significant potential in providing value-added products from the by-products of chemical pulping processes. As Antikainen et al. (2017) state, significant development is still needed in order to move the biorefinery status beyond the current production of fibres, energy and some chemicals to a broad spectrum of products and thorough utilization of wood components. The selected biochemical applications are based on wood extractives (Crude Tall Oil), hemicelluloses (lactic acid) and lignin (lignin derivatives), thus fostering the idea of full valorization of lignocellulosic biomass.

The main objective is to introduce the formation of value chains for selected biochemicals as well as provide assessment of the market conditions including essential supply and demand drivers. In addition, future outlook and potential barriers for the products are also discussed. Moreover, these biochemicals provide an opportunity to illustrate the different time scales of these products (Fig. 6.). As Rajendran et al. (2016) point out, the European pine chemicals industry has existed for over 80 years, serving as an example of a business that is currently producing commercially valuable by-products from the kraft pulping process. On the other hand, hemicellulose and lignin parts are not yet widely commercialized as product bases, hence providing an opportunity to further analyze the potential for the cases utilizing these feedstocks.

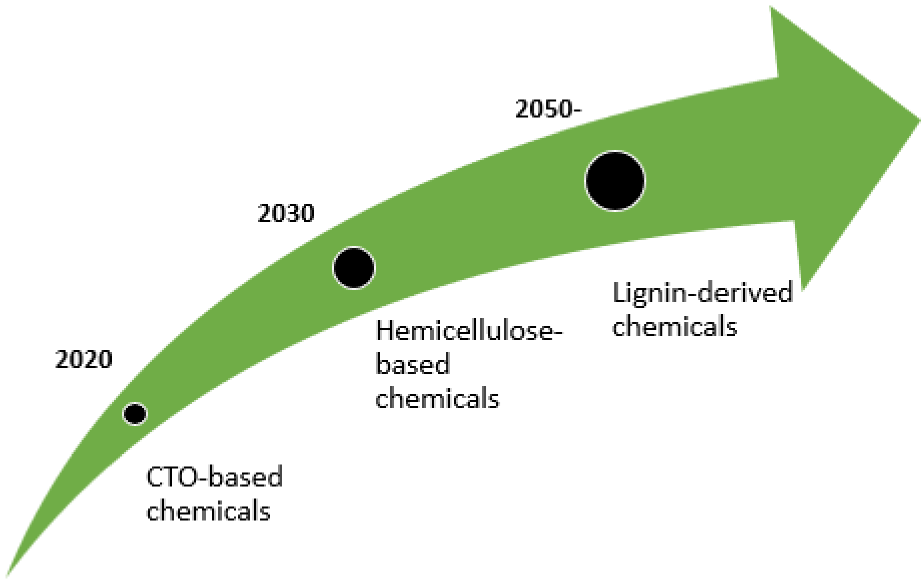

Fig. 6. The illustration of the timescale of different commercially viable wood-based biochemical feedstocks. Source: Schipfer et al. (2017), Pöyry (2018)

2.3.1 Crude Tall Oil

CTO is a commercially valuable by-product of Kraft chemical pulping production process which is further processed and upgraded by CTO biorefineries into a wide array of products including adhesives, coatings, fuel additives, mining and oilfield chemicals, lubricants, rubber emulsifiers, surfactants, paper size chemicals and fuels (Rajendran et al., 2016). According to Peters and Stojcheva (2017), the word 'tall' means 'pine' in Swedish, indicating that CTO in mainly generated by pulping process of softwood (pine) trees although a relatively small share of CTO is also produced from hardwood trees. CTO industry is a great example of resource efficiency through its cascading use of biomass, ensuring that economic and social value of the biomass is maximized through product processing and upgrading along the downstream value chain (Rajendran et al., 2016).

As stated by Peters and Stojcheva (2017), when producing pulp, wood chips are treated with white liquor for delignification of wood in order to produce pulp. Wood extractives react with this cooking liquor and after the cooking stage, pulp and weak black liquor (residual used cooking liquor) are separated during the washing step. Weak black liquor contains valuable pulp cooking chemicals; thus, they are extracted in the recovery boiler before being re-used in the pulping process. Weak black liquor has a floating top layer of soap containing solid materials and it must be removed due to its strong foaming properties. According to Aro and Fatehi (2017), weak black liquor needs to be evaporated to achieve a dry solid content of 20-30% for optimal removal of the soap layer. The evaporation process results in strong black liquor and the removed soap layer called Crude Sulphite Soap (CSS) forms the base material for CTO. The quality of CSS varies because of differences in chemical composition and the residue needs to be cleaned and homogenized to uniform the material. Homogenized CSS is further acidulated to CTO and the remaining 'mother liquor' containing sodium is often fed back into the Kraft process. Therefore the CTO facility extracting CTO from CSS is usually integrated with the pulp mill albeit there are also a number of stand-alone CTO plants in North America (Peters and Stojcheva, 2017).

Peters and Stojcheva (2017) name four main categories for the uses of CTO: process fuel in the pulp mill lime kiln, distillation into a variety of products, usage as a component of petroleum extraction drilling fluid or for phosphate mining and renewable diesel production. Some minor other uses exist, too. At present, CTO distillers use a major part of the available feedstock. CTO can be further broken down to four main fractions in a vacuum distillery: Tall Oil Fatty acid (TOFA), Tall Oil Rosin (TOR), Distilled Tall Oil (DTO) and Tall Oil Pitch (TOP). The quality of CTO is generally measured on its rosin acid content and acid number (AN) value; high AN value indicates a high proportion of rosin acids, thus making it more favorable to CTO distillers.

According to Mccormick (2018), tall oil rosins are the most valuable components of CTO with the 25-35% overall proportion. The uses for TOR include manufacturing of fortified rosins, paper size, printing inks, adhesive resins, rubber chemicals and soldering fluxes. Tall oil fatty acids represent around 20-40% of CTO and they are used similarly as vegetable oil or tallow-based fatty acids, e.g. soaps, cleaners, detergents, oil field chemicals, surfactants and emulsifiers. In addition, TOFA is also used for renewable diesel production. Distilled tall oil (10-15% share) is produced from a blend of TOFA and TOR, thus combining the advantages of both components. The rosin content can vary depending on the application and the current uses include metal working fluids, oil field chemicals, soaps and alkyd resins. Lastly, with a 20-30% share, tall oil pitch is the heavy fraction of CTO. It is mainly used for energy production in tall oil refineries but also for asphalt additives, ore flotation, corrosion inhibitors and biofuel production.

The CTO market has moderately small volumes due to its origin from global chemical softwood pulping sector. This is simultaneously the main supply driver for CTO, bringing the total CTO production potential to roughly 2,6 million tonnes per year (Peters and Stojcheva, 2017). Still, the total potential could be slightly increasing due to global softwood pulping capacity growth, specifically in the US and Scandinavia. It is estimated that around half of the global chemical pulp mills with CTO potential have CTO facility albeit this varies regionally; for instance, the majority of European pulp mills (excluding Russia) have an on-site CTO plant (Peters and Stojcheva, 2017). Practically all Scandinavian mills acidulate CSS into CTO, additionally Russian CSS is also mainly acidulated. Alternatively, a notable amount of CSS in the US is not being acidulated, making the estimation of global production more challenging. The consensus estimate of the current actual production lies between 1,8 and 2,0 million tonnes, depending on the market demand for CTO (Peters and Stojcheva, 2017). However, Rajendran et al. (2016) notify that due to its finite volume as a by-product of kraft pulping, any increase in demand for CTO does not lead to an increase in supply.

The total demand for CTO is largely based on the chemical sector while market floor prices are determined by either heavy fuel oil prices (Europe) or natural gas prices (US). As stated earlier, CTO-based end use products can be divided into four main categories, namely distilling, biofuels, oil drilling and direct energy with their relative shares of 80%, 13%, 5% and 1%, respectively (Peters and Stojcheva, 2017). According to Rajendran et al. (2016), the European downstream industries for CTO-based intermediate chemicals provide a significant market for CTO refiners. The market attractiveness for several CTO applications differs in terms of the compound annual growth rate and market volume; the largest EU pine chemicals application areas include rubber and tyre manufacturing, coatings industry and the adhesives and sealants market. The rising demand for bio-based alternatives widens the market opportunities for pine-based chemicals. In addition, policy incentives supporting bio-based chemicals could encourage the substitution of fossil-based products and promote the EU goals to increase the share of bio-based chemicals.

However, current policy alignments regarding the CTO utilization for biofuels have generated confrontations between CTO distillers and biofuel producers. According to the current Renewable Energy Directive (RED) [2009/28/EC] and the directive to reduce indirect land use change for biofuels and bioliquids [(EU)2015/1513], CTO is listed as a feedstock which will be considered to be twice its energy content for its contribution towards the 2020 final consumption of energy in transport in Member States. Mccormick (2018) states that this has made tall oil as an interesting feedstock for renewable diesel, thus creating concerns over CTO availability. As Rajendran et al. (2016) point out, CTO volumes remain limited due to the kraft pulp production volumes, hence making it a very limited raw material for energetic use. The total EU biodiesel & renewable diesel production in 2018 is estimated to be around 16 000 million liters (Flach et al., 2017) while the EU wide availability of CTO is limited to approximately 650 000 tonnes per year. Additionally, Rajendran et al. (2016) further notify that in a hypothetical situation where all available CTO produced in the EU were to be converted to biodiesel, it would make just a negligible contribution to the total EU transportation fuel levels.

Moreover, Rajendran et al. (2016) state that for the base year 2015, the estimated economic added value for the pine chemicals industry including CTO refiners and downstream operators was at least 4 times more when comparing to the 100% biofuel production from CTO. Additional conclusions for the comparison disclose that the full life cycle utilization of CTO produces slightly lower greenhouse gas (GHG) emissions compared to the production and consumption of the pine-based biofuel. The impact on the generated employment for the upstream pine chemical industry and the downstream CTO industry was approximately 9100 jobs while the biofuel production was estimated to generate 400 jobs, making the total employment impact significantly larger for the combination of pine chemicals industry and the downstream value chain. Furthermore, according to Aro and Fatehi (2017), a biodiesel production plant using tall oil would require over 120 000 m^3 of CTO per year for an economically viable production. Based on the limited supply of CTO and the socio-economic and environmental impact assessment, the European pine chemicals industry appears to be more competitive CTO utilizer compared to biofuel producers, thus creating a strong case for the wood-based biochemicals production.

2.3.2 Lactic acid

Lactic acid is a bio-based chemical produced via dedicated pathway. It is used in several food processing and industrial applications and has the potential of becoming significant volume commodity-chemical intermediate made from renewable carbohydrate feedstock. Possible uses for lactic acid range from biodegradable polymers, oxygenated chemicals, plant growth regulators, solvents and specialty chemical intermediates (Crnomarković et al., 2018). It is currently commercially available albeit the technology readiness level between different production technologies varies. Production from fermentation of sugars from lignocellulosic material ranges from TRL3 to TRL5, hence making it the least advanced production system. Lactic acid production from fermentation of sugars from sugar crops or starch crops is fully commercially available (European Comission, 2014).

Lactic acid can be produced commercially either by bacterial fermentation of carbohydrates or via petrochemical routes using coal and crude oil to produce acetaldehyde (Fig. 7.). According to Higgins (2011), lactic acid exists in two isomeric forms known as L-lactic acid and D-lactic acid. Optically pure D- or L-forms can be produced via biological routes while synthetic (petrochemical) routes result in a racemic mixture containing each isomer with the same quantity. Currently the majority of lactic acid production is done by fermentation process instead of chemical synthesis. This results from hazardous raw materials (hydrogen cyanide), high energy intensity (triple distillation), the lack of pure L-form isomer and high manufacturing costs with the synthetic route (Crnomarković et al., 2018). In addition, Tokiwa and Calabia (2008) state that optical purity of lactic acid is needed for the physical properties of PLA. When PLA is produced from pure L-isomer or D-isomer, the polymer is crystalline and more stable compared to the amorphous polymer from a racemic mixture.

The production of lactic acid can provide an opportunity for the forest industry to create value added products from hemicellulose. As stated in Walton et al. (2010), hemicellulose is burned along with lignin to generate power and steam in the kraft pulp mills. However, hemicellulose does not have as good heating value as lignin (16,7 MJ/kg vs. 26,5MJ/kg) (Bruijnincx et al., 2016), hence supporting the idea of hemicellulose extraction in order to increase the value derived from lignocellulosic feedstocks. The sugars obtained from woody biomass could be partly utilized for the lactic acid feedstock.

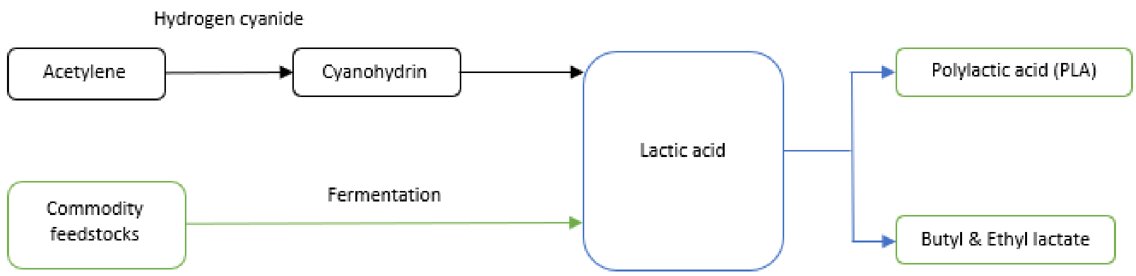

Fig. 7. Value chain of lactic acid containing feedstock and key derivatives. Source: Adapted from Crnomarković et al. (2018)

Global demand for lactic acid in 2016 totaled around 1200 kta and the expected demand for 2030 equals over 4000 kta. The highest demand for lactic acid was in food and beverage applications in 2015 while polylactic acid manufacture represented the second largest end use of lactic acid. However, PLA manufacture is estimated to be the leading application of lactic acid in 2020 with demand for environmentally friendly packaging products combined with enhanced technological development. Regional demand for lactic acid in 2016 was strongest in China with 48% share of total demand, followed by Americas with 29% share, rest of Asia with 13% share and Europe with 10% share (Crnomarković et al., 2018).

L-lactic acid is the most coveted form and the majority of the demand focuses on it. According to Boomsma et al. (2015), it is used in animal fodder at the lowest level of purification. High purity L-lactic acid can be applied e.g. for antimicrobial cleaning, cosmetics and pharmaceuticals. In addition, D-lactic acid serves as a building block for PLA polymers.

Lactic acid industry is rather consolidated with two large producers, Corbion and NatureWorks, with a production capacity of 225 kta and 180 kta, representing 24% and 19% of the total supply, respectively. Other producers are mainly Asian (Hebei Jindan, Shenzhen

BrightChina, Chongqing Bofei, Wuhan Sanjiang) which represented 11%, 9%, 8% and 7% of total supply in 2013, respectively. New capacities of lactic acid and PLA are forecasted in Asia region, providing the fastest growth with demand from end user markets. New production capacities for lactic acid and PLA are not been indicated in Europe albeit growing demand for sustainable, bio-based plastic combined with stricter policies on the usage and release of toxic and non-degradable chemicals in the environment could provide opportunities for PLA-based polymers and lactic acid-based chemicals (Crnomarković et al., 2018).

Lactic acid illustrates the switch from fossil to bio-based industry. With cheaper and safer feedstock, less energy intensive production and optically pure product, bio-based lactic acid offers more competitive solution in relation to synthetic production. Lactic acid faces rising demand especially from food & beverages sector as a pH regulator and preservatives. Additionally, growing cosmetic industry is expected to fuel industry expansion with increasing number of manufacturing base by companies including Unilever, Johnson & Johnson and P&G (Grand View Research 2018).

Crnomarković et al. (2018) point out that the need for sustainability, biodegradability, recyclability, and green packaging among consumers is projected to drive global PLA usage further. PLA is both bio-based and biodegradable and offers notable reductions in GHG emissions (30-70%) and energy use compared to fossil counterparts such as polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET). While PLA suffers from performance drawbacks compared to conventional plastics, various manufacturers are engaged in improving properties of PLA including impact strength, flexibility, stiffness, barrier properties, thermal stability, increase degradation rate, as well as reduce production costs, which can create significant market potential (Grand View Research 2018).

However, despite mature manufacturing technology, PLA is not yet a cost competitive alternative for packaging compared to fossil alternatives for similar markets. The price for PLA was traded around 2600 €/ton in western Europe at the end of 2017 whereas PET market price was estimated at about 1100 €/ton. Cost competitiveness improvements are fundamental for PLA in order to be at least comparable to its fossil equivalents PP, PE and PET. Feedstock costs and production costs must be further reduced as well as performance characteristics have to be improved (Crnomarković et al., 2018).

Overall, bio-based lactic acid production offers several opportunities from both techno-economic and environmental factors. Bio-based lactic acid is more cost-effective compared to the synthetic one and both lactic acid and PLA manufacturing processes are mature. Additionally, strong demand for sustainable, non-toxic and biodegradable solutions can give an edge for lactic acid and its derivatives. On the other hand, several issues must be confronted in order to improve specifically the competitiveness of PLA. Its performance in packaging and food applications underperforms when compared to fossil alternatives. It is also essential to improve the recyclability of PLA for it to feature in circular economy. Considerations of the sustainability of biomass feedstocks must also be made. As Juturu and Wu (2016) notify, lactic acid production from starchy materials competes with food and feed supply, thus creating a need for inexpensive, abundant and renewable carbon source. This feature could provide an opportunity for forest-based lignocellulosic feedstock as the production technologies continue to develop further.

2.3.3 Lignin applications

Lignins are polymers of aromatic alcohols which bind the cellulose fibers (Hagberg Börjesson and Ahlgren, 2015).They represent the main aromatic renewable resource with cellulose as they are found in most terrestrial plants in the approximate range of 15 to 40% dry weight. Hence, they offer great potential of being alternative feedstock for the elaboration of chemicals and polymers. As Ragauskas et al. (2014) point out, large quantities of lignin are yearly available from numerous pulping processes but large-scale industrial processes using plant polysaccharides have traditionally burned lignin for power generation. Laurichesse and Avérous (2014) identify that one of the major problems still limiting lignin's utilization is the unclearly defined structure combined with its versatility according to the origin, separation and fragmentation processes. Current uses for lignin can include filler or additive applications but it is rarely employed as a raw material for chemical production.

Lignin may still be an excellent candidate for chemical manufacturing due to its highly functional character.

According to Chakar and Ragauskas (2004), the objective of chemical pulping process is to remove enough lignin to separate cellulosic fibers from one another and produce pulp suitable for further refining. Lignin can be extracted from other lignocellulosic parts by physical, chemical and biochemical treatments. Vázquez et al. (2000) denote that lignin's structural and chemical characteristics depend on the pulping reagents and conditions used during its extraction. Two main categories of the commercially viable extraction processes are sulfur and sulfur-free processes (Table. 2.). As Laurichesse and Avérous (2014) point out, sulfur processes (sulfite- and Kraft pulping) produce lignosulfate- and Kraft lignin while sulfur-free processes (solvent- and soda pulping) produce organosolv- and soda lignin.

Sulfur lignins are primarily produced by pulp and paper industries. The Kraft process and sulfite processes differentiate from each other in regard to the mixture of chemicals used in the process. The Kraft process is based on sodium hydroxide and sodium sulfide while the sulfite process uses aqueous sulfur dioxide for cooking and calcium sodium, magnesium or ammonium for base. These processes produce black liquor that will be further acidified to recover both lignins (Laurichesse and Avérous, 2014).

Despite the high sulfur environment during the kraft lignin extraction, its sulfur content is low, typically less than 1-2%. It also contains a high amount of condensed structures and a high level of phenolic hydroxyl groups. New, more efficient lignin removal processes for kraft pulping have been investigated, e.g. Lignoboost process by Innventia which is now owned by Valmet Corporation. Conversely, lignosulfates contain a significant amount of sulfur. Lignosulfates are water-soluble and have higher molar mass than kraft lignin, leading them to be the technical lignins most exploited for several industrial applications, e.g. binders, dispersing agent, surfactant, adhesives and cement additives (Laurichesse and Avérous 2014).

Table 2. Comparison of lignin extraction processes. Source: Adapted form Mccormick (2018)

	Origin	Pre-treatment	Separation	Sulphur content	Purity	Stage
Kraft lignin	Softwood, hardwood	Alkaline	Precipitation or ultrafiltration	Moderate	Moderate-High	Industrial
Lignosulfonate	Softwood, hardwood	Acid treatment	Ultrafiltration	High	Low	Industrial
Soda lignin	Herbaceous	Alkaline	Precipitation or ultrafiltration	Free	Moderate-Low	Industrial
Organosolv	Hardwood, softwood	Acid	Dissolved air flotation, precipitation	Free	High	Pilot

Laurichesse and Avérous (2014) point out that sulfur-free lignins represent an emerging class of lignin products with their structure being close to the native lignins, hence showing interesting properties that can make them as an attractive source of low-molar mass phenol or aromatic compounds. According to Hage et al. (2009), organosolv process produces pure, high-quality lignin which is primarily unaltered and less condensed than other pre-treatment lignins. It is also soluble in many organic solvents and hydrophobic, thus showing potential for applications in the fields of adhesives, fibres, films and biodegradable polymers. Laurichesse and Avérous (2014) state that the most common organosolv processes are based on ethanol/water pulping (Lignol®) and pulping with acetic acid (Acetosolv). Additionally, CIMV Company has developed the Biolignin® with the extraction process being based on a mixture of formic acid, acetic acid and water.

Furthermore, as stated by Laurichesse and Avérous (2014), soda-based cooking methods are based on hydrolytic cleavage of the native lignin but resulting in a relatively chemically unmodified lignin. An example of this approach uses a specific method for the precipitation of lignin for black liquor by adjusting pH value with mineral acids (Green Value SA). However, soda lignin can present high silicate and nitrogen contents due to its extraction procedure, leading to lower purity (Mccormick, 2018).

As presented in Fig. 8., there are two different groups of the main lignin uses: no chemical modification (i.e. directly incorporated into matrix) and chemical modification. According to Laurichesse and Avérous (2014), chemical modification of lignin can be further classified into three main categories: fragmentation, new chemical active sites and hydroxylfunctions modifications.

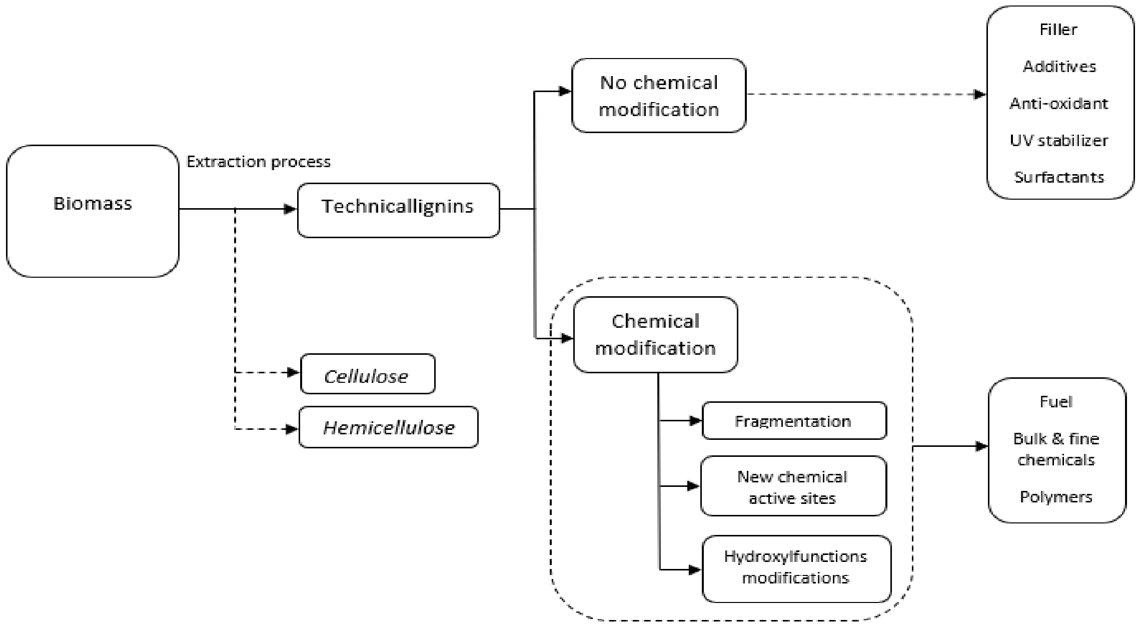

Fig. 8. Value chain of lignin with or without chemical modifications. Source: Adapted from Laurichesse and Avérous (2014)

Fragmentation or lignin polymerization enables the utilization of lignin as a carbon source or to cleave lignin structure into aromatic macromers. This process aims to undo the nature's biosynthesis and thus there has previously been focus on methods to add value and use lignin without modifying its intrinsic structure. Lignin has a variety of functional groups: hydroxyl, methoxyl, carbonyl and carboxyl groups, and its structural complexity has hindered prior higher end uses of lignin. However, to surpass this limitation, lignin can be modified to increase the range of functional groups' applications. Several modifications including nitration, amination, alkylation/dealkylation, carboxylation and halogenation have been investigated. Ultimately, lignin can also be chemically modified by functionalization of hydroxyl groups. Its phenolic hydroxyl groups are the most reactive functional groups, significantly effecting the chemical reactivity of the material. After hydroxylfunctions modification, most phenolic hydroxyl groups are converted into aliphatic hydroxyl units, leading to more reactive hydroxyl groups to become readily available (Laurichesse and Avérous, 2014).

From the perspective of Finnish biorefining industry, especially kraft lignin presents a major opportunity as it is produced in kraft pulp mills. According to Mccormick (2018), interests towards lignin separation are growing. Since increasing pulp production leads to large excesses of lignin, its separation provides a way for kraft pulp mills to debottleneck the recovery boiler while aiming for production increases. Mccormick (2018) suggests that separating and removing 10-30% of lignin from the black liquor before recovery boiler could be one of the best ways to utilize surplus energy in pulp mills. In addition, global kraft pulp production capacity approximates 150 Mt/a, creating great potential for large volume kraft lignin production.

Lignin supply has been largely based on ligno-sulphonates. Grand View Research (2018) states that this product segment accounted for over 88% of global share in 2015. However, Bruijnincx et al. (2016) point out that the pulp production via sulfite process is declining, hence resulting in a lower availability of lignosulfates in the future. According to Laurichesse and Avérous (2014), around 95% of the over 70 million tons of lignin produced globally was burned while only the remaining 5% was used for commercial applications, e.g. additives, dispersants, binders or surfactants. Yet, it must be notified that only a very limited amount of the lignin produced is actually isolated and available. Lignin is also a by-product from 2nd generation bioethanol production. The production of ethanol requires only 40% of the dry lignin to meet the heat/power demand, thus surplus lignin produced could become available for higher value usage. It can be estimated that around 0,5 kg of lignin per kg of ethanol will be produced (Bruijnincx et al., 2016).

According to Mccormick (2018), the most potential end uses for kraft lignin today are fuel oil and natural gas replacement in lime kilns (150-250 €/t), cola replacement in CHP (100-250 €/t) and fuel oil and natural gas replacement in industrial and district heat production (200-300 €/t). However, lignin has multiple promising end-uses under development with 5-10 years to full commercialization including carbon fibre (high value, high volume), polymers and composites and component in various chemicals (resins and glues). Grand View Research (2018) presents that the lignin market is expected to benefit from R&D investments made by significant manufacturers for the development of improved technologies for lignin extraction, and development of lignin applications in aromatics. One of the main growth drivers are the construction industries, primarily across the developing economies in Asia Pacific.

Current successful modifications of lignin include the industrial elaboration of vanillin, DMSO and lignin-based polyol for the synthesis of polymer. Still, the development of lignins has been detained by its intrinsic properties, the variability of the resource, polydisperse molar masses and hyperbranched structures. This highlights the importance of using high-purity lignin for its high-value utilization. It must also be acknowledged that the isolation, purification and drying of lignin requires major investments, thus adding to its price. Bruijnincx et al. (2016) suggest the cascade approach to lignin valorization with several stages on the depolymerization process, making full use of the complete lignin input. The first step would concentrate on extracting targeted and isolatable valuable chemicals as the high value of the products would still enable an economically feasible process. The lignin left could be subjected to later, harsher cleavage steps focusing on cleaving more recalcitrant bonds. After these treatments, any heavy residues left could be used e.g. for fuel or burnt for the generation of heat and power.

Lignin is receiving greater attention as the aromatic compounds from oil exploitation become rarer and costlier. This creates drivers for the biorefinery concept and further lignin valorization. With a high interest in developing an economically viable route for lignin-based chemicals and biobased polymers, possibility of its depolymerization into phenol and BTX would provide a wide variety of fine and bulk chemicals produced from lignin. However, according to Pohjakallio (2015), the most significant bulk petrochemicals with oil as the main feedstock, namely, ethylene, propylene, butadiene and benzene, toluene and xylene (BTX), are globally produced at a rate of around 310 million tons/year. Berlin and Balakshin (2014) notify that global purified lignin production at chemical pulp mills could potentially replace a maximum of ca. 2% of the volume of main petrochemicals. This figure could somewhat increase if the emerging lignocellulose biorefinery industry producing biofuels and chemicals could make more biomass available. The BTX strategy represents a long-term opportunity and as Bruijnincx et al. (2016) state, even with attractive price premiums (around $1200 per tonne), it remains to be seen if viable cost-efficient valorization processes can be developed.

Although fundamental research has historically focused on lignin conversion to chemicals, materials and fuels, the effort has not yet been translated into common practice. According to Ragauskas et al. (2014), catalysts for a change in this paradigm could comprise of bioengineering of lignin to reduce recalcitrance of the cell walls to bioprocessing and facilitate ease of recovery and conversion. In addition, advances in analytical chemistry and computational modelling in order to couple genetic engineering developments of lignin to targeted physical and chemical properties combined with biomass pretreatment technologies facilitating lignin recovery and catalytic modifications that yield tailored chemical and physical properties could be involved. Bruijnincx et al. (2016) suggest also a databank containing fingerprints of all kind of lignins which would support lignin application research materially and increase the chances for successful lignin-based value chains. Ultimately, cross-sectional partnerships between forest sector, agro sector and chemical sector are needed in in order to accomplish full valorization strategies.

2.4 Current policy drivers for biochemical sector

As Philippidis, Bartelings, and Smeets (2018) state, the policy making of EU aims for the utilization of biomass to achieve a competitive, low-carbon and sustainable model of growth and employment. However, Carus et al. (2011) adduce that the investment in industrial biotechnology and biorefineries has remained low. The industrial material use of biomass has not been supported by the political and economic framework in the EU, the opposite of biofuels and bioenergy which have seen rapid expansion in the EU region. Carus et al. (2016) note that bio-based chemicals compete for the same feedstock with energy uses and the difference between the EU policy frameworks have been distinct. Biofuels and bioenergy have received high support in R&D, pilot and demonstration plants as well as strong ongoing support during commercial production (including quotas, tax incentives and green electricity regulations). The lack of adequate policy framework and comparable support for bio-based chemicals risks the investment activity from private sector and distorts markets regarding the feedstock availability and costs.

Some of the key policies covering the EU bioeconomy sectors are Renewable Energy Directive (RED), Indirect Land Use Change (ILUC), Horizon 2020 (H2020), European Industrial Bioenergy Initiative (EIBI), Bio-Based Industries Joint Undertaking (BBI JU) and NER 300 programme (funding for innovative low-carbon energy demonstration projects). However, as pointed out by Taylor et al. (2015), potentially only H2020 and BBI JU impact upon the biochemicals sector.

Horizon 2020 is a research and innovation programme implemented by European Union. It offers nearly 80 billion euros of funding for over seven years (2014-2020). As European Commission (2013) notes, H2020 promises more breakthroughs, discoveries and world-firsts by facilitating the transition of products from labs to markets. Furthermore, with the overall objective to accelerate the conversion of fossil-based European industries to low carbon, resource efficient and sustainable ones, the building of a broad knowledge base and the development of relevant biotechnologies is essential. According to European Commission (2013a), H2020 focuses mainly on three elements:

- Transforming current fossil-based processes into resource and energy efficient biotechnology-based ones
- Establishing reliable, sustainable and appropriate supply chains of biomass, byproducts and waste streams and a wide network of biorefineries throughout Europe
- Supporting market development for bio-based products and processes, taking account of the associated risks and benefits

Taking actions on the demand side may be help for new market openings for biotechnology innovations. Within the H2020, standardization and certification at the European and international level are seen as a requirement for the determination of bio-based content, product functionalities and biodegradability, thus generating a need for research activities supporting product and process standardization and regulatory activities in the field of biotechnology.

Bio-Based Industries Joint Undertaking, established on 6 May 2014, is the body commissioned to implement the public-private relationship between the European Union and the Bio-Based Industries Consortium. According to BBI JU (2018), the total contributions from both partners form an aggregate of 3,075 billion euros with almost 75% contributed by the industry. The aim of the BBI JU is to bring relevant stakeholders together in order to establish European innovative bio-based industries as a competitive sector, including primary production, large industry, SMEs, clusters, trade associations, academia, RTOs and end-users.

The objective of BBI JU is to strengthen the development of a sustainable and competitive bio-based industry in Europe which is based on advanced biorefineries. Furthermore, BBI JU (2018) lists three objectives for the initiative:

- Demonstrate technologies that enable new chemical building blocks, new materials and new consumer products from European biomass and which replace the need for fossil-based inputs
- Develop business models that integrate economic actors along the whole value chain from supply of biomass to biorefinery plants to consumers of bio-based materials, chemicals and fuels, including through creating new cross-sector interconnections and supporting cross industry clusters
- Set up flagship biorefinery plants that deploy the technologies and business models for bio-based materials, chemicals and fuels and demonstrate costs and performance improvements to levels that are competitive with fossil-based alternatives

Bio-Based Industries Joint Undertaking operates its programme as the catalyst to enable the European Union and bio-based industry to align their strategy and vision while respecting Horizon 2020 principles of openness and transparency while also paying attention to synergies and complementarities with other initiatives.

In addition to the European key policies, BioPreferred, managed by the U.S. Department of agriculture, serves as an example of a policy program to promote the bioeconomy. According to USDA (2009), the BioPreferred program aims to increase the purchase and use of bio-based products while stimulating economic development, creating new jobs and providing new markets for farm commodities. The incremental development and use of bio-based products may reduce the nation's reliance on petroleum as well as increase the use of renewable agricultural resources and contribute to reducing adverse health impacts.

According to USDA (2009), the two major components of the BioPreferred program are:

- A preferred procurement program for bio-based products applicable to Federal agencies and their contractors
- A voluntary labeling program for the marketing of bio-based products to the general consumer. The U.S. Department of Agriculture (USDA) is the lead Federal agency in the implementation of the BioPreferred program

The procurement program for bio-based products directs all federal agencies to purchase bio-based products which are identified by USDA. The object of the voluntary labeling program is to provide information to consumers about the product's bio-based content. When a bio-based product meets the USDA criteria, the certification can be applied. The USDA Certified Biobased Product label insures consumers that the manufacturer's claims concerning the bio-based content are being met.

According to Dieckhoff, El-Cichakli, and Patermann (2015), many EU members are also implementing country or regional-specific bioeconomy strategies. However, the variation in the political aims and measures of the individual countries as well as underlying motivations have created somewhat different strategic approaches. Some countries (e.g. USA, Japan and Germany) have published governmental, coordinated and pervasive bioeconomy strategies while other countries such as Italy or Canada, are relying firstly on industrialized or regional initiatives. In addition, Dieckhoff et al. (2015) state that the difference in natural resource abundance affects the strategic standpoints; many European countries with few natural resources and strong industrial structure view the bioeconomy from its innovative potential and the opportunity for industrial renaissance. However, while North American countries classify medical-biotech innovations as part of the bioeconomy the EU does not. The European Union prioritizes firstly the replacement of fossil fuels and focuses secondarily on achieving a technological advantage in biomass processing with new methods to create novel bio-based products.

3. Theoretical framework

One of the classical research fields in the innovation literature is the analysis of radical innovation processes and their effects on the fundamental transformations of the entire economic sectors. Innovation processes have multiple consequences concerning entire value chains in the particular field as well as policy makers and the society as a whole. Therefore, it remains important to acquire an improved understanding about innovation processes albeit it may prove to be demanding at times. The complexity of the underlying innovation processes pose different challenges when analyzing them. Markard and Truffer (2008) point out that innovation processes typically depend on the co-development of new socio-technical configurations, new market structures, new actors and new institutional settings. Additionally, processes concerning innovations and larger transitions tend to depend on spatial and historical context conditions leading to challenges with theory building and research methodologies aiming at generalized empirical findings.

The analysis of the fundamental transformation processes has been approached from at least two different perspectives. Innovation scholars have focused either on the prospects and dynamics of a specific innovation with a potential to contribute to major transitions in status quo. An alternative approach is the investigation of broader transition processes at a more aggregated level. Both perspectives could support a deeper understanding of radical innovation and transformation processes and lead ideally to similar outcomes while also being complementary to each other. There are two major strands of conceptual and empirical work in the innovation literature addressing the two standpoints: innovation system approaches and the multi-level framework. Additionally, Markard and Truffer (2008) introduced a concept of integrated framework combining both approaches in order to ease the translation of results from multi-level studies.

Multi-level framework stems particularly from the context of strategic niche management which facilitates the regime shifts by creating and supporting specialized niches for the experimental technologies, such as wood-based biochemicals. According to Hermans (2017), multi-level framework can be utilized for explaining the spread of local knowledge and innovation from the micro levels to the higher macro levels in society. Geels (2002) points out that with the multi-level framework, a distinction between market and technological niches, socio-technical regimes and socio-technical landscapes can be made. These levels form the micro, meso and macro levels for the bottom-up approach of socio-technological expansion (Fig. 9). As stated by Hermans (2017), higher scale level of the multi-level framework will lead to more aggregated components and relationships between actors causing slower dynamics between them. New innovations and practices can easily change at the micro level but the flexibility will eventually taper off, making transitions to take even decades at the macro level.

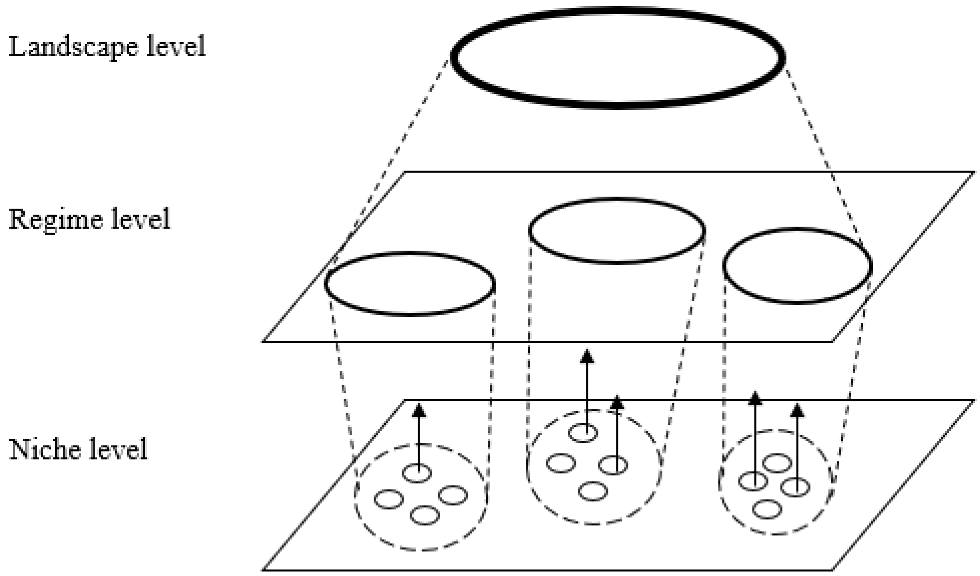

Fig. 9. Hierarchical structure of the multi-level framework. Source: Adapted from Geels (2002).

The micro level consists of niches which form the environment for the emerging novelties. They stand for the local level of the innovation process and form conditions where new technologies can be emerged and developed. Niches create a habitat for the actors to advance with the new technology and the development of the new markets without the selection pressures from the incumbent markets (Hekkert et al., 2007). According to Hermans (2017), one can identify three vital internal processes within a niche for its development over time:

1. The articulation and subsequent convergence of visions
2. Learning and experimentation
3. The building of relational networks

The first process represents the convergence or divergence of different actors' strategies, expectations, beliefs and practices. The second process refers to the learning and experimentation of the niches and the third process emphasizes the importance of the existence of the most salient actors within the niche. Networking contributes also to the learning and experimentation by the collaboration of stakeholders from different fields of activities.

As stated by (Geels, 2005), niches can be distinguished into two different types depending on their selection environment. Market niches refer to situations where the selection criteria occur due to unconventional application contexts or consumer preferences. This requires that both producers and users recognize the potential of the new technology. Another type of niches are the technological niches. According to Geels (2005), technological niches are provided with resources from public subsidies or strategic private investments in order to create experimental projects involving different actors. The main difference between these constructs is the level of recognition of the new technology; in technological niches, the potential advantages concerning the technology are still tentative and possibly not shared among the niche stakeholders (Markard and Truffer, 2008).

Socio-technical regimes form the meso level within the multi-level framework. It is an extended version of technological regime as the term socio-technical regime does not only emphasize engineers or scientists but also different stakeholders (businesses, policy makers, end users, societal interest groups etc.) that share the rules and practices that constitute a regime. Technologies, actors or actor networks are not part of the regime themselves but technologies and products embody the rules and actors perform the routines that make up the regime (Markard and Truffer, 2008). According to Geels and Schot (2007), niches and socio-technical regimes resemble each other with their structures even though with a distinction in their size and stability. Regimes comprise of large and stable communities as well as stable and well-articulated rules.

Regimes represent the selection environment when considering technological development in certain fields or sectors, hence posing a substantial barrier for the diffusion of radical innovations. When explaining difficulties for radical new innovations to fit in, the concept of socio-technical regime can therefore be facilitating. Different actors can be conditioned by the incumbent conditions and ways. Additionally, existing technical infrastructure has an impact on the direction of new investments and innovations (Hermans 2017). For a niche to become a part of the existing regime, it has to be compatible with the regime or have a means to resolve regime's bottlenecks. The regime shift may occur when the current regime is weak. Such transition includes both vertical and horizontal changes for the incumbent value chain and it possibly even leads to an entire reconfiguration of the established value chain (Markard and Truffer, 2008).

The macro level of the multi-level framework is formed by the socio-technical landscape. It can be represented as the external environment of factors and processes influencing both regimes and niches while not being under direct influence of the actors in the regimes and niches. The socio-technical landscape can therefore be defined as a set of heterogeneous factors including macroeconomic factors, wars, cultural and normative values, environmental issues etc. (Geels, 2002). Markard and Truffer (2008) suggest viewing landscape as a set of residual factors. They impact innovation and production processes but are not influenced by the outcomes of these processes on a short to mid-term basis.

The transition pathways and the interplay between the different levels of niches, regimes and landscapes can be explained with the multilevel framework. As Geels and Schot (2007) point out, there is a presumed bias of bottom-up, niche-driven transition processes. Thus, propositions for four different transition pathways have been identified (Geels and Schot, 2007):

1. Transformation path
2. De-alignment and re-alignment path
3. Technological substitution
4. Reconfiguration pathway

Transformation path refers to a situation when moderate landscape pressure arises while niche innovations are not yet fully developed. This disruptive change on the landscape creates pressure on the regime and leading the regime actors to reorientate. In this case the niche innovations are not capable of taking the advantage of the pressure on the regime level due to their insufficient development. Instead, old regimes can be adjusted with symbiotic niche innovations that do not disrupt the regime's basic architecture (Geels and Schot, 2007).

When landscape level encounters divergent, large and sudden changes, increasing landscape pressure can make the regime actors to lose faith (Hermans 2017). This leads to de-alignment of the current regime. Again, in the absence of fully developed niches there is no clear substitute for the late regime. Multiple niche innovations co-exist competing for resources and attention. One of the niche innovations will ultimately stand out and reconstruct the core for the re-alignment of the new regime (Geels and Schot, 2007).

Technological substitution refers to a similar starting position as in the de-alignment/re-alignment path. Disruptive landscape pressure occurs and leads to the current regime being replaced. Technological substitution differs with the niche innovations' readiness level. Niche innovations have been developed to a level where they can break through and replace the existing regime, provided that landscape pressure occurs. Without the pressure, the current regime remains stable, leading the regime actors to largely ignore niche innovations. When regime tensions take place and the fully developed innovation enters mainstream markets, actors of the incumbent regime will defend their position by investing in improvements (major difference between the de-alignment situation). In case of regime replacement by the new innovation, knock-on effects and broad regime changes ought to be expected (Geels and Schot 2007).

Reconfiguration pathway occurs when symbiotic, fully developed niche innovations are adopted by the regime, subsequently leading to architectural adjustments in the regime level. These innovation adoptions are motivated by economic considerations and most regime rules are left unchanged, resembling the transformation pathway. This situation expands to the reconfiguration pathway as adopted novelties lead to further adjustments and adoptions of new niche innovations. Hence, with the assistance of landscape pressure, this will gradually accumulate to the growth of new regime out of the old regime (Geels and Schot, 2007).

These different pathways are not mutually exclusive as shifts between pathways may occur. Geels and Schot (2007) thus present a sequence of transition pathways, referring to a situation where disruptive landscape pressure initiates transition with transformation, followed by reconfiguration and possibly leading to substitution or de-alignment and re-alignment. For instance, Vandermeulen et al. (2012) suggest that the most plausible pathway regarding the bio-economy transition would likely follow the sequence of transition pathways. This transitional pathway starts with transformation pathway, proceeded by technological substitution or de-alignment and re-alignment pathway.

Innovation system perspective provides another approach for transformation processes. It is an analytical framework aimed to study prospects and dynamics of a particular innovation, thus providing more extensive view of the occurrence. Innovation system concept is a practical tool for analyzing novel and radical technologies as well as institutional and organizational trends necessary for progression of emerging technological fields.

Conceptually, innovation systems can be defined at different levels for different purposes of analysis. According to Edquist (2009), they are composed of networks including actors and institutions developing, diffusing and using innovations. Innovation systems can be compared and evaluated by the system functions in order to derive policy recommendations (Bergek et al., 2005). These system functions emphasize the fact how the innovation system works (Markard and Truffer, 2008). Broadly speaking, a system can be defined as a set of components interacting with each other while working toward a common objective (Carlsson et al., 2002).

As Markard and Truffer (2008) state, innovation systems have been defined at different levels depending on the intention of the underlying analysis. The first concept regarding the innovation literature has been the national systems of innovation. Several other approaches have been proposed later, including regional systems of innovation, sectoral systems of innovation, production systems and technological systems. In the context of this research, radical innovation processes will be the main interest, thus leading to concentrate specifically on the technological systems concept.

Since innovation system is comprised of components interacting with one another, Markard and Truffer (2008) suggest it to be "a model of reality designed for analytical purposes", implying an evident distinction with the system and its environment. When defining different systems, their structure can be used to describe their characteristics. In the case of innovation systems, organizations and institutions can be considered to be the main components. According to Edquist (2009), organizations (actors) can be perceived as formal structures with conscious creation and explicit purpose. Typical actors encompass different firms, universities, research facilities, public agencies (governmental and non-governmental), venture capitalists, etc. Institutions represent the sets of common rules or laws as well as habits, norms or established practices. These can be seen as the rules of the game. The distinction made between actors and institutions facilitates the discrimination for "the rules of the game" and "the players" in the game.

The delineation of the innovation system is essential. It has to be possible to discriminate between the system in question and the external world, i.e. to identify the system boundaries.

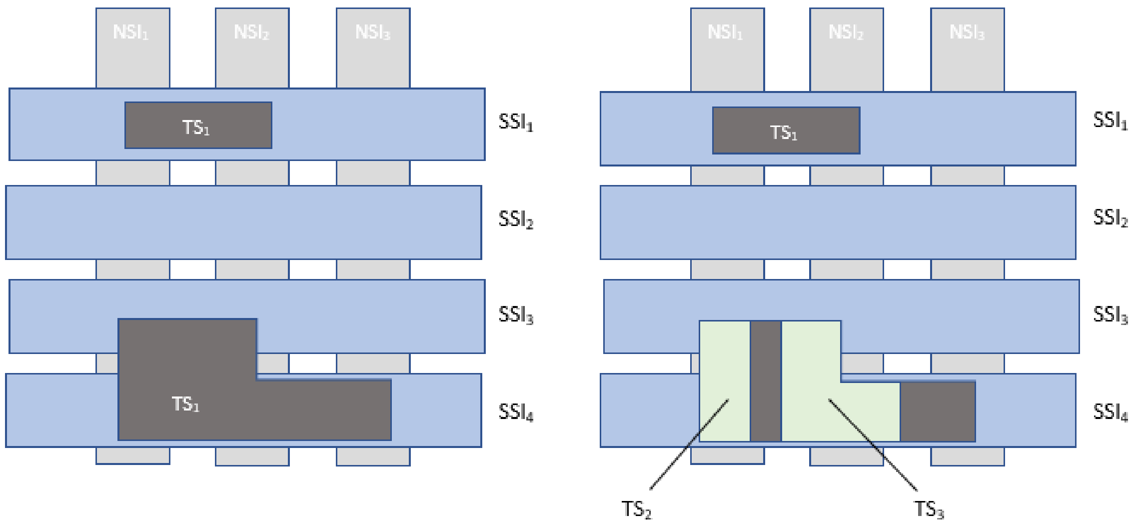

Fig. 10. Illustration of the relationships between national (NSI), sectoral (SSI) and technological (TS) systems of innovation as well as the delineation of two sub-technological systems. Source: Adapted from Markard and Truffer (2008).

As Markard and Truffer (2008) point out, system delineation depends initially on the chosen system concept. Fig. 10. shows the relationship between national, sectoral and technological systems. The delineation of national systems is based on a spatial basis with the assumption of organizations and institutions being defined by influences and interactions on a specific region. Conversely, sectoral systems are founded on industrial structures and may cross regional boundaries. Technological systems are combinations of interconnected sectors or industries possibly cutting across regional and national levels. They can also be parts of a larger technological system, delineated on a spatial and sectoral basis, e.g. to compare the performance of technological systems in different countries.

Carlsson et al. (2002) propose further three levels of analysis for the delineation of technological systems: knowledge field (what falls within a particular knowledge field), product or an artefact level or set of products (multi-product analysis). Still, it may turn out to be difficult to delineate the technological system due to the lack of precise borders of a competence field as well as the dynamic character of the system. In the case of system comparison, the influence between the systems may lead to a situation where they cannot be treated and analyzed separately any longer (Markard and Truffer, 2008).

The contribution of the system components to the system's aggregate target can be referred as system functions or activities (Bergek et al., 2005). Functional analysis of the innovation system is a way of separating content from the structure; to accentuate what the system does or how it works. Functions may be accomplished by many different components and each component may influence several functions. According to Markard and Truffer (2008), system structure can influence its function and contrariwise. Still, structurally different systems may resemble each other in terms of functions and vice versa, leading to a lack of optimal structure for a well performing system. Regardless, system performance can be measured by comparing different systems since the key to system performance comparison is their evaluation with respect to their functions.

While the overall function of the innovation system is to develop, diffuse and use innovation, various authors have suggested the inclusion of different functions or activities, so-called sub-functions. Several empirical and conceptual articles have proposed different sets of sub-functions (e.g. Bergek et al. (2005), Hekkert et al. (2007)). This research uses the functions defined by Hekkert et al. (2007):

1. Entrepreneurial activities
2. Knowledge development
3. Knowledge diffusion through networks
4. Guidance of the search
5. Market formation
6. Resources mobilization
7. Creation of legitimacy

Entrepreneurial activities refer to the entrepreneurs turning the potential of new knowledge, networks and markets into specific actions in order to generate new business opportunities. These activities can relate to new entrants as well as incumbent firms trying to diversify their business strategy and product portfolios. Experiments can provide essential knowledge regarding the technology functioning under different environments along with reactions from different stakeholders. Active entrepreneurial participation can also provide a good indication of the innovation system's performance; when the system is functioning well, it will presumably lead to a thriving atmosphere for entrepreneurial activities (Hekkert et al., 2007).

As Bauer et al. (2016) articulate, knowledge development and diffusion can be considered to be the fundamental resources for innovation processes, leading to emphasize the R&D efforts from both industrial and academic participators. Hekkert et al. (2007) suggest mapping out this function by using R&D projects, patents and investments in R&D as indicators. In addition, increase in technological performance can be measured with so-called learning curves. The diffusion of knowledge through networks is important in enhancing information exchange between stakeholders. When R&D setting is combined with government, competitors and market, policy decisions should be in line with the latest technological insights. Further, R&D programs should reciprocally be affected by changing norms and values, leading diffusion through networks to be a prerequisite for "learning by interacting" (Hekkert et al., 2007).

Hermans (2017) refers guidance of the search to be the selection function alleviating the convergence in expectations regarding different technological options. Limited resources force the selection of specific foci among several technological options to be forwarded. According to Hekkert et al. (2007), guidance of the search also indicates for technological change's dependence on societal preference changes, leading to influence R&D priority setting. When public discourse emphasizes the positive aspects, it is likely to stimulate technology development and vice versa.

Market formation pays attention to the early stages of commercializing new technologies. Innovations may initially be badly adapted for their ultimate uses, leading the diffusion of novel innovations to be slow. A protected space for these applications will be a necessity with possibilities ranging from temporary niche markets, competitive advantages (e.g. favorable tax schemes) or minimum consumption quotes in order to promote a demand for new products (Bergek et al., 2008b).

Mobilizing both financial and human resources will be needed to knowledge production and innovation system creation. Thus, resource mobilization is a significant input for the knowledge development and entrepreneurial activities. Funding for R&D programs enables both the development of novel technologies and testing them in niche experiments. The objective for the new technology is to become a part of the incumbent regime or even displace the current regime. This may create resistance from established actors and hence it is essential to create legitimacy for the novelty. Social acceptance can be gained with the assistance from guidance of the search, mobilization of resources and creation of advantageous market conditions (Hekkert et al., 2007).

One of the core applications for the innovation system framework is the identification of system weaknesses (the divergence between current and desired functional patterns). Analyzing weaknesses provides an instrument for the recognition of the key blocking mechanisms affecting the innovation system. This enables essential information for both actors within the systems as well as to the ones outside it (Bergek et al., 2008a). Moreover, Hellsmark et al. (2016) propose the analysis of the system strengths. Deviating from most prior innovation system literature, the system strength perspective intents to determine what the system actors can achieve by themselves. System strengths can also provide motivation for political actions while indirectly addressing system weaknesses by further building on the identified strengths. Regardless, proper addressing of system weaknesses remains essential as failures in this process may lead to negative feedbacks on the key system functions

The comparison of innovation system concept and multi-level framework provides several similarities between them as they are comparable in terms of basic concepts and theoretical roots. As Markard and Truffer (2008) adduce, actors, networks and institutions form conceptual components on basic concept level for both technological systems and niches. However, niches separate from technological systems as supportive institutions are not part of the niche since they represent external elements. Regime level differentiates conceptually from technological systems and niches by being the rule-set, i.e. emergent and collective outcome unable to be changed at will (Geels, 2002).

Regimes can be defined at the industry or sector level, indicating a high level of aggregation. This definition applies also to mature technological systems. Emerging technological systems deviate from the former abstract as they can generally be analyzed at medium level of aggregation including several application contexts of the new technology. Overall, technological systems are being constructed from multiple niches as niches refer to single application context. When analyzing these aforementioned concepts for their role on the innovation process, niches can be seen as the creators and protectors of the radical innovations. On the other hand, regimes represent the guidance of the innovation process, generating incremental improvements that strengthen the regime. Technological systems do not make the distinction between radical innovations and incremental innovations. The focus is either on the innovation part (generation, diffusion and use of new technologies) or production part (diffusion and utilization of established technologies) (Markard and Truffer, 2008).

As Markard and Truffer (2008) point out, both approaches possess their strengths and weaknesses making them applicable to different perspectives on innovation processes. The multi-level framework explains transition processes by the reciprocal effect between the stabilizing regime level mechanism and destabilizing landscape pressures joined with niche level innovations. However, the analysis of roles and strategies of different actors is compromised in this approach, thus affecting the perception of resource distribution and how they explain the network development. Overall, the multi-level framework can be perceived as a concept for the explanation of technological transitions focusing on the system's environment.

On the one hand, the innovation system perspective concentrates more detailedly on structural and functional analysis, leading this approach to be more potent dealing explicitly with corporate strategies and agency. On the other hand, innovation systems can be perceived as inward orientated, thus overlooking the system's environment and possibly resulting in erroneous conclusions when identifying blocking mechanisms affecting the innovation system. With the less systematic processing of the external environment, this approach may also miss other influential processes or novel technologies and products emerging in competing systems. Hence, the innovation system perspective is lacking the explanatory power with respect to the technological transitions (Markard and Truffer, 2008).

Although the innovation system concept and the multi-level framework have different approaches regarding innovation processes and socio-technical transitions, they also have complementary strengths. According to Markard and Truffer (2008), a combined framework could provide an edge over the merits of each approach. While the development of this kind of combined framework would necessitate several empirical test cases to ensure its relative advantages over the aforementioned concepts, such framework could ease the translation of results from studies with different innovation approaches.

Fig. 11. illustrates the interaction between the two approaches where focal innovation system connects with different socio-technical regimes as well as with other innovation systems. The nascent innovation system could face barriers formed by the incumbent regimes

deteriorating the development and diffusion of the innovation. Furthermore, novel innovation system may also challenge the current regimes with its potential substitutional potency. The focal innovation system will also likely interact with other innovation systems by either competition or complementation. Additionally, the innovation system is generally comprised by a number of niches which provide testing fields for new technologies while also serving as a networking platform for actors from different innovation systems.

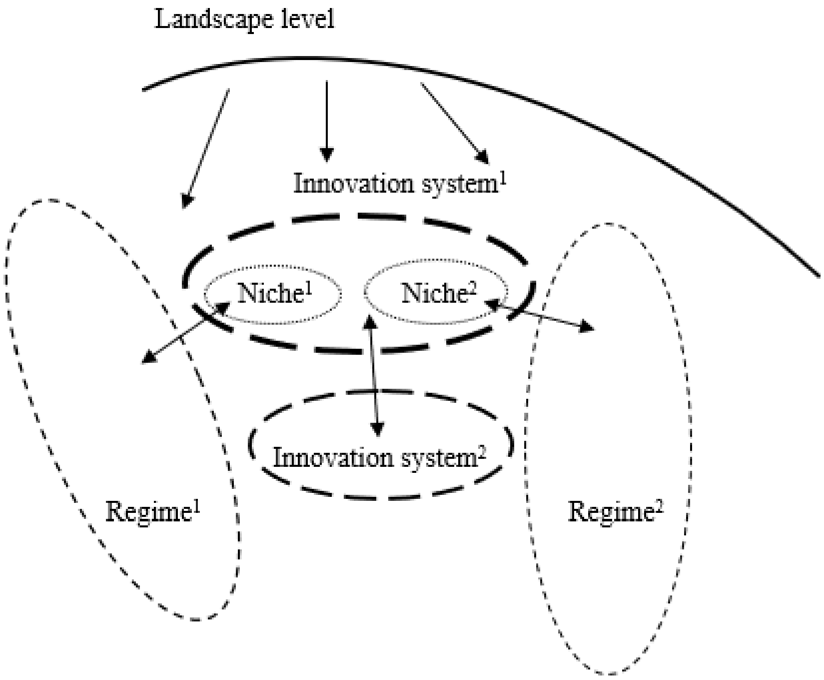

Fig. 11. The interaction between the innovation system approach and the multi-level framework. Source: Adapted from Markard and Truffer (2008).

The explicit advantage of the combined framework could thereby be the act of bundling the two different innovation approaches and utilizing both concepts for the analysis. However, as Markard and Truffer (2008) point out, the combined framework would still need further conceptual advances. Particularly a broad analysis of dynamics and social construction processes as well as implications for policy and strategy formulation and performance comparisons between different innovation systems are necessary so that the two traditions could combine their strengths.

4. Materials and methods

As product range and market actors in the field of bio-based chemicals are widely heterogenous, the identification of the drivers and barriers regarding the successful adoption of bio-based products remains challenging. This creates a specific need for the analysis on the acceptance of bio-based chemicals in order to provide insights into the sector-wide stakeholders. This study has the main focus on the market acceptance of the Finnish business-to-business sector (B2B) including standpoints from the forest industry, the chemical industry and the research facilities. However, the geographical context and the focus of this study is mainly about the Finnish markets but several features of the existing forest-based chemicals markets, inter alia limited domestic markets, globally diffused value chains and EU-level legislation and regulation, are forcing to widen the spatial perspective to some extent. While the key research objective of the study is to concentrate particularly on the forest biomass-based biochemicals, the research results can also be applied to an extent to bio-based chemicals in general.

The chosen research method for this study is interview research which is further complemented with a literature review, aiming to provide an overview of the new wood-based biochemical products, to identify the market potential of selected products or product groups, and to analyze this effect under the renewal of the Finnish forest industries. Interviews were chosen as the research method because of the novelty of the research topic which reduces the availability of other data sources. Furthermore, expert interviews enabled the collection of in-depth information of the thoughts and experiences of the industry operators regarding the current phenomenon. The expert interviews aim to explore the structural drivers and barriers of the selected markets and evaluate their relative impact on the competitiveness and development of the biochemical products. Expert interviews are based on a semi-structured interview which were conducted by person-to-person interviews. The interview structure is based on the technological innovation systems (TIS) functions (Markard and Truffer 2008), aiming to provide a sight to the potential problems hindering the development of the TIS. Furthermore, the interview questionnaire consisted of three different parts including 7 questions aimed at locating the systemic drivers and barriers of the wood-based biochemical TIS.

The selection of interviewees was based on their differing positions in the chemical production value chain, thus combining different actors from various industries with the objective of providing a thorough overview of the visions regarding bio-based chemicals.

Table 3. The presentation of the interviewees.

Expert ID	Position in the value chain	Primary sector
1. Senior management	Upstream	Forest sector
2. CEO	Upstream	Forest sector
3. Senior management	Upstream	Forest sector
4. Senior management	Midstream	Chemical sector
5. Senior management	Midstream	Chemical sector
6. Senior management	Downstream	Chemical sector
7. Researcher		Chemical sector
8. Researcher		Chemical sector

During the year 2018, semi-structured thematic interviews were conducted with 8 company executives and industry experts representing various forest-based industries and interfacing sectors (Table 3.). The criteria for the selection of the interviewees were that they represented companies which either are developing or involved in the development of novel wood-based chemical products or are potential users of the wood-based biochemical bases. The interviews were also complemented with an academic perspective. As this research addresses the structural change in forest industry from a Finnish perspective, one essential requirement for the selection of the interviewed companies was that the firms have also operations in Finland. The anonymity of the interviewees has been retained on request.

The analysis of the data was based primarily on the general inductive approach (Thomas, 2006), aiming to summarize the raw data, establish a relation between the research objectives and the obtained data as well as develop a framework of the processes existing in the data. Moreover, the research objectives were derived from the innovation system approach presented by Markard and Truffer (2008) and multilevel framework by Geels (2002), also corroborating the data analysis and providing the basis for the further interpretation of the obtained data. The collected data from the interviews was summarized which was then followed by the iteration process aimed at identifying and forming an overall picture of the development of the industry. This process was also supported by a simultaneous literature review regarding both innovation studies as well as the research into biochemicals and the renewal of the forest industry.

4.1 Validity and reliability

Possible limitations regarding the research in general may originate, inter alia, from researcher's presence during data gathering, personal biases and idiosyncrasies, volume of the data or lacking rigor (Anderson, 2010). However, efforts were made in order to reduce the impact of the limitations to the outcome of the study. The questionnaire design for the purpose of this research was formulated in cooperation with the supervisors of the thesis. Although relatively small (Marshall et al., 2013), the sample size of interviewees provided sufficient information to analyze the phenomenon with comprehensive manner. Due to the very early stage of the examined topic related to the wood-based biochemicals, it was somewhat challenging to find suitable interviewees. Still, the data began to noticeably saturate (Marshall et al., 2013), so that further data collection would not have necessarily brought added value considering the scope of this study.

5. Results

The identified system strengths and weaknesses for the Finnish wood-based biochemical TIS are presented in the Fig. 12.

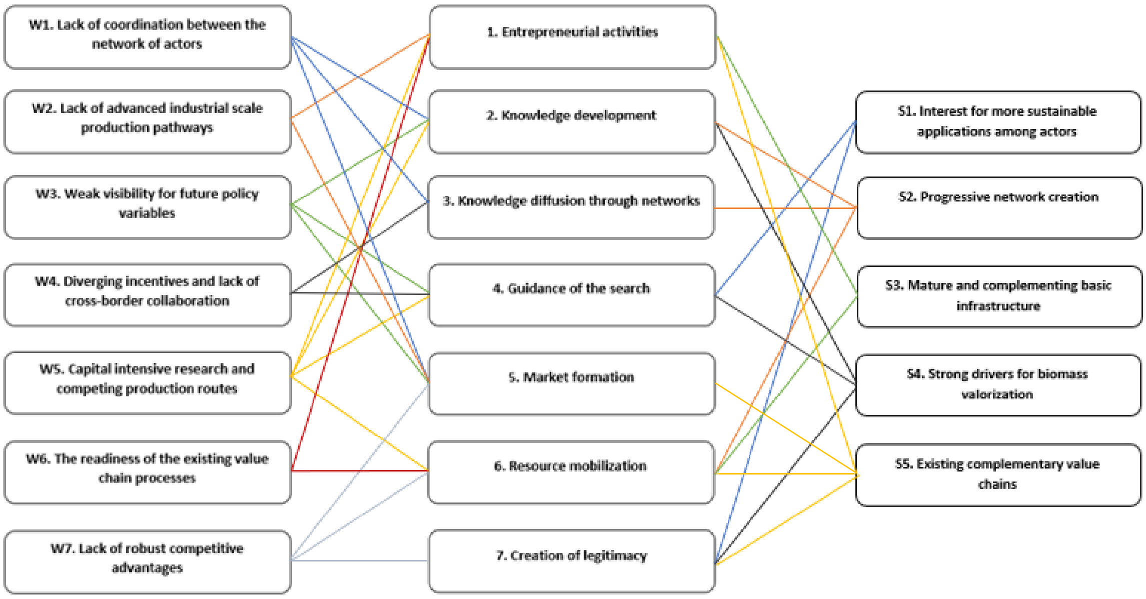

Fig. 12. Illustration of the system strengths and weaknesses of the Finnish wood-based biochemical TIS.

5.1 System strengths

The Finnish wood-based biochemical TIS possesses several systemic strengths that can further accelerate the development of this niche. The analysis of the system resulted in five identified strengths:

S1. Interest for more sustainable applications among actors
S2. Progressive network creation
S3. Mature and complementing basic infrastructure
S4. Strong drivers for biomass valorization
S5. Existing complementary value chains

The first strength relates to the growing attraction of the more sustainable applications among the different stakeholders within the potential biochemicals value chains. Due to the comprehensive consensus view on the sustainability aspects, industry stakeholders considered that introducing and adopting bio-based products enhances their circular economy and environmental acceptability. Furthermore, industry actors have recognized a favorable atmosphere for the promotion of bio-based products, thus favoring further establishment of novel biochemicals.

In addition to the external trends, the bio-based chemicals manufacturers identified growing interest and demand for bio-based alternatives from the customer base. Although the bio-based chemicals were recognized to be able to offer unique and superior properties beyond the limits of fossil-based alternatives, this demand was also increasingly driven by the bio-based factor. Hence, the emergence of renewable material bases can be identified as a connecting factor between the forest and chemical industries. The interest for more sustainable applications among actors strengthens particularly the functions *guidance of the search* and *creation of legitimacy*.

The second strength addresses the progressive network creation between the stakeholders in different industries. Industry participants recognized increased communication between the forest and chemical industries in recent years. Some published collaborative partnerships between forest and chemical sector companies were addressed while also obtaining new know-how in the form of business acquisitions functions as a way to transfer forest industry companies to the learning curve was identified. While the forest industry's traditional cooperation has been established especially with the crude oil industry, biochemicals stakeholders identify the emergence of second generation biorefineries and the cross-sectoral industrial ecosystems they enable (e.g. Äänekoski bioproduct mill) as a prominent measure for further collaboration and networking between forest and chemical industries, strengthening specifically the functions *knowledge development*, *knowledge development through networks* and *resource mobilization*.

The third strength represents the existing, mature infrastructure which could be complementary for the manufacturing of wood-based biochemicals. Industry stakeholders notified that the already existing infrastructure can potentially serve as a platform for new applications, thus reducing risks associated with investing in new production unit with technologies not yet commercialized. Forest industry participants recognized that another driver incentivizing the emerging production of biochemicals may come from the demand to increase the efficiency of the older production plants. The additional by-products increasing the revenue from the pulp mill were seen to create an economically attractive opportunity for the producers provided that the costs related to conversion activities do not offset the positive economic effects from the manufacturing of new bioproducts. Overall, the mature and complementing infrastructure can be considered to strengthen especially the functions *entrepreneurial activities* and *resource mobilization*.

The fourth strength relates to the current strong drivers supporting the full valorization of biomass. Biochemicals industry stakeholders in its entirety share the positive view on further processing of biomass into higher value-added products. This strength affiliates also with the need for efficiency increases and gradual replacement of declining traditional products. According to the interviewed industry experts, the investment potentials for biorefinery products and value of woody biomass are considered to increase over the next ten years, thus driving the valorization of biomass further, strengthening particularly the functions *knowledge development*, *guidance of the search* and *creation of legitimacy*.

The fifth system strength is associated with the existing complementary value chains. Both forest and chemical industry stakeholders adduced that the most promising biorefinery products including biochemicals are considered to be somewhat compatible with current production chains, thus enhancing the possibility for future large-scale production. Furthermore, already existing crude tall oil industry was brought up as an example of a commercially successful wood-based biochemicals industry which could also function as a specific roadmap for biochemical novelties as well as elucidate the collaboration between the chemical industry and the forest industry. Hence, the complementary value chains contribute to the strengthening of the functions *entrepreneurial activities, market formation, resource mobilization* and *creation of legitimacy*.

5.2 System weaknesses

In addition to the identified system strengths, the Finnish wood-based biochemical TIS encompasses several system weaknesses, hence forming blocking mechanisms within the innovation system. With the addressing of the system weaknesses, it is possible to decrease the negative feedbacks on the key system functions as well as concentrate the policy assessment more effectively. The analysis of the system led to seven identified system weaknesses:

- W1. Lack of coordination between the network of actors
- W2. Lack of advanced industrial scale production pathways
- W3. Weak visibility for future policy variables
- W4. Diverging incentives and lack of cross-border collaboration
- W5. Capital intensive research and competition with existing production routes
- W6. The readiness of the existing value chain processes
- W7. Lack of robust competitive advantage against incumbent actors

The first system weakness addresses the lack of coordination between the different stakeholders within the system. This hindrance concerns different industry actors as well as local and supranational administrative organs. Industry actors underlined the lack of direction between the different actors, for instance: “It can be seen everywhere that this is not an old stabilized business such as paper production where companies work together, for example, with standardization matters … Here on biochemical side such standardization has not come about but everyone uses their own terms and customers have no idea what’s happening.” (Senior management, company 1.).

Several participants with varying interests regarding the direction of the system’s development alongside a vast number of possible biochemical novelties may deflate the system actors’ focus, thus affecting negatively the system evolution from the development phase. Although the actors have common goals regarding sustainable development, it was emphasized that achieving technological compatibility does not necessarily lead to commercial collaboration between the operators. These obstacles hinder the development of the functions *knowledge development, knowledge development through networks* and *market formation*.

The second weakness relates to the lack of advanced industrial scale production pathways for biochemicals. Although several identified system strengths (e.g. S3 and S5) emphasize the opportunities provided by the complementary infrastructure and value chains for the biochemical production, industry experts pointed out that the techno-economic feasibility of the solutions causes problems for industrial-scale biochemical production. Additional issue comes from the amount of raw material feasible to be taken out of current processes. Furthermore, the gap between the demonstration phase and high-volume manufacturing acts as a barrier in the short term. Industry experts also stressed the importance of factoring in the heterogeneity of the product mixture. This has a direct effect on the further compatibility of different product mixtures, for instance, when considering drop-in chemicals from lignin. These weaknesses with the lacking large-scale production pathways effect especially the functions *entrepreneurial activiti*es and *market formation*.

The third weakness is associated with the weak visibility for the future policy variables. Industry stakeholders stated that forming reliable forecasts becomes more difficult as legislation and political guidance are recognized to be somewhat unpredictable variables, reducing visibility to the future. Additionally, legislation is also seen as a partial bottleneck for innovation. For instance, setting boundaries for the raw material usage instead of market-driven utilization may direct valuable resources to inefficient applications: "Policies and legislation can create barriers for innovation … for example when legislation begins to determine the purpose for which the raw materials are to be used." (Senior management, company 4.).

Furthermore, industry stakeholders stated that the insufficient certification systems regarding biochemicals is a factor explicitly hindering the introduction of bio-based novelties. Moreover, the governmental support for operational business activity is seen as undesirable as industry stakeholders perceive that market pull should come from the formation of real markets. Overall, these weaknesses have an effect on the functions *knowledge development*, *guidance of the search* and *market formation*.

The fourth weakness represents the diverging incentives as well as the lack of cross-border collaboration between the industry actors. Apart from the policy makers, the industry participants identified diverging interests and absence of common ground especially at the firm-level. These differing incentives are also seen to affect the parties' transition from one industry to another, weakening the conditions for cooperation. In addition, industry actors experienced that a clear distribution between the biomass supplier and the chemical engineering specialists exists. Forest industry value chains have also traditionally lacked the access to other companies to enter forest companies' own process areas and hardly any sharing of expertise has taken place due to the industry's competitive nature. These barriers have weakened specifically the functions *knowledge diffusion through networks* and *guidance of the search*.

The fifth weakness addresses the issues regarding capital intensive research and competition with the existing product routes. As notified by the industry experts, forest industry is considered to be conservative industry with rather low research and development intensity: "Even though pulp production is close to chemical industry, it doesn't work according to the basic patterns of the chemical industry … when thinking about the R&D intensity between the industries, chemical industry spends easily 3-5 times more on the R&D operations from the revenues than the forest industry." (Researcher, company 8.) . Enabling the production of new wood-based innovations requires both large investments and extensive R&D activity, leading to competition with other possible investment opportunities. Industry stakeholders stated that the risk factors associated with the investments to the new product areas acted somewhat as a barrier compared to the investments in known technologies. Moreover, the allocation of development funds on relatively low-risk items was seen as hampering radical innovation.

Additionally, it was noted that much of the development work concerning the new innovations has taken place in research institutes, leading to lower in-house development intensity with the forest industry sector: “The is lack of technological know-how, the development may have been relying too much on research institutes and their resources while forest industry companies have been too conservative.” (CEO, company 2.). Furthermore, the sufficiency of the raw material base as well as the discourse regarding which materials will eventually produce the best end products create challenges for industry operators. These obstacles hinder especially the development of the functions *entrepreneurial activities*, *knowledge development*, *guidance of the search* and *resource mobilization*.

The sixth weakness affiliates with challenges concerning the readiness of the existing value chain processes. Although the mature and complementing infrastructure as well as the existing complementary value chains have been considered as system strengths, the compatibility of the downstream value chain processes emerges as a challenge. Industry experts notified that in the case of dedicated chemicals, the entire downstream processes may have to be converted while also having end products with differentiated characteristics. Another highlighted significant variable relates to the compatibility of bio-based products with the current recycling infrastructure. These barriers with the current value chain processes may require investments in existing manufacturing equipment as well as in end-of-life management systems, raising the threshold for switching to bio-based solutions in customer processes. Additionally, investments result in dependency to raw materials which to some extent are impacted by policy variables. Hence, these obstacles weaken specifically the functions *entrepreneurial activities* and *resource mobilization*.

The seventh weakness highlights the lack of robust competitive advantage against the incumbent actors. Even though the industry stakeholders identified growing interest in more sustainable applications, there is not yet a significant market for these products. Biochemicals are seen to be mostly a western occurrence while no special interest exists in the rest of the world. After all, customers are looking for the cheapest option and are not necessarily willing to pay bio-premium for otherwise equivalent product. Hence, bio-based chemicals require some additional value proposition, such as improved performance in order to compete with the fossil-based alternatives.

Furthermore, it was stated that the demand and vision for the introduction of bio-based products in the value chains originates from the brand owners. Although the push comes from the biomass producers, the value chain actors in between do not have incentives for the utilization of biochemicals unless the brand owners start driving their deployment. Additionally, bioproducts are not seen as the toughest competitor for the traditional crude oil at least in the short term. On the other hand, a distinct increase in the price of crude oil may drive the interest with the bio-based alternatives albeit the total share of bio-based chemicals in the chemical industry are still seen to account for only a few percent of the total industry volume at the most. Overall, these weaknesses affiliated with the competitive advantages are seen to hinder the functions *market formation*, *resource mobilization* and *creation of legitimacy*.

6. Discussion

The delineation of the wood-based biochemical technological innovation system (TIS) requires that additional bioeconomy pathways have to be taken into consideration. As Purkus et al. (2018) state, a strong interdependency exists between established and innovative pathways, leading them to compete for the same resources, e.g. biomass, financial support and human capital. This pressure is further increased by the incumbent, fossil resource dominated chemicals regime as well as other associated regimes. However, other interacting complementary systems, e.g. biofuel production in biorefineries, may also be an accommodative factor for the emergence of the biochemical sector. According to Hellsmark et al. (2016), it is important to create overlaps and iterations between different types of pilot and demonstration plants to foster technology development, allowing the moves of going back and forth between different plants where various designs, actor networks and value chains can be tested and evaluated. Fig. 13. illustrates the interactions between the focal TIS and other relevant innovation systems and regimes.

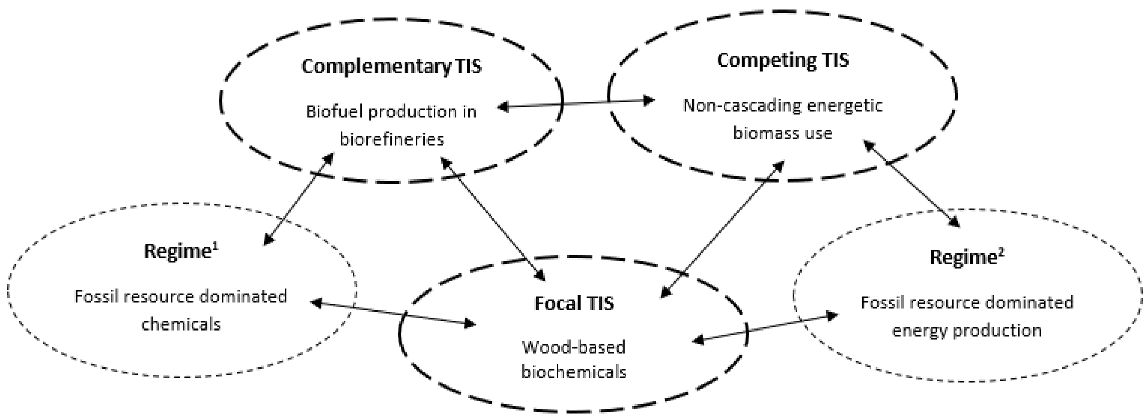

Fig. 13. Examples of the interactions between the wood-based biochemicals and other significant innovation systems and regimes. Source: Purkus et al. (2018), Markard and Truffer (2008).

Furthermore, an essential part of the examination of the wood-based biochemical TIS and the system's functional performance assessment is to link the functions with relevant inducement and blocking mechanisms. As Bergek and Jacobsson (2014) adduce, the inclusion of solely the most important linkages is critical. Additionally, one must also consider that different mechanisms can influence several functions both directly and indirectly. Hellsmark et al. (2016) point out that existing system strengths do not usually render any explicit need for policy intervention, thus directing the policy actions for the mechanisms blocking the system.

The results from the interviews with industry experts highlighted both positive drivers as well as several barriers affecting the system, forming an overview for the further development of the innovation system. Although the systemic strengths and weaknesses encompass a wide range of variables, the summation reveals a few themes whose impact on the development of the system can be considered very significant. According to Hekkert et al. (2011), in order to locate the system functions forming the barriers, it is necessary to relate the presence and fulfillment of the system functions to the phase the systems is in. As the large-scale production of wood-based biochemicals is still at the early stages, the review of the functional patterns representing the wood-based biochemical TIS focuses on the pre-development- and development phases (Fig. 14.). Moreover, the point of convergence of the analysis is specifically on the functions *knowledge diffusion through networks* (F3) and *guidance of the search* (F4) as these parts play a significant role in the early development of the entire system.

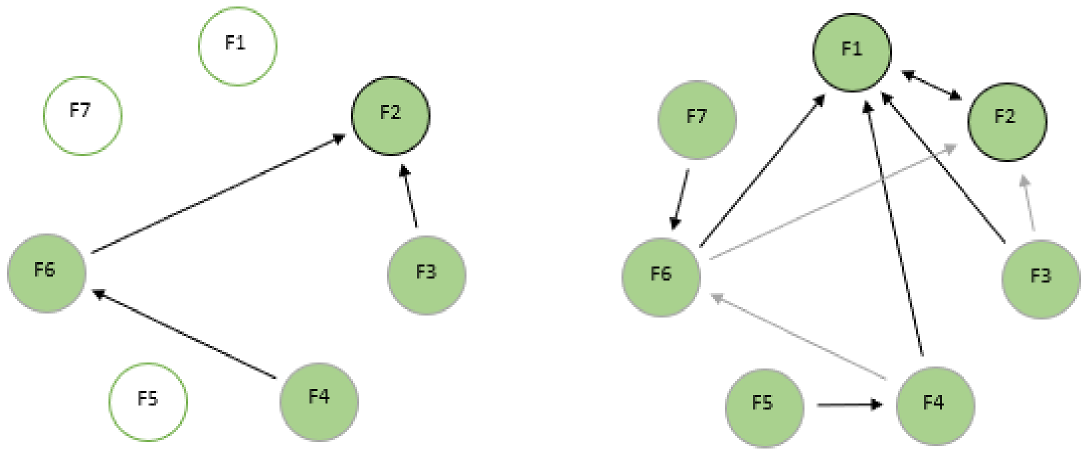

Fig. 14. Representation of the functional patterns in the pre-development- and development phases. Source: Adapted from Hekkert et al. (2011).

As shown in the Fig. 14., the knowledge exchange between the system actors as well as the regulations, visions and expectations of governments and key actors act as a base for both pre-development phase and development phase, creating a need for a more detailed examination of the forces affecting these functions. In order to address the system weaknesses through the policy instruments, these approaches could be partially build on the current system strengths (e.g. Hellsmark, Mossberg, et al. 2016), thus promoting already existing positive effects on the system.

Knowledge diffusion through networks incorporates the increasing communication between the forest industry and chemical industry in the recent years which has also led to some published cooperation projects such as Stora Enso and Virdia in 2014 (Nasdaq OMX, 2014)), thus functioning as a way to transfer forest industry companies to the learning curve and creating a strengthening effect on this systemic function. Furthermore, bio-based raw materials are seen as a significant incentive from the point of view of chemical industry by the industry experts. Hekkert and Negro (2009) state that the R&D setting in a heterogenous context combining government, competitors and market should be consistent with latest technological insights while being also affected by the changing norms and values. Hence, the potential shift in the industry actors' current R&D portfolios towards more sustainable solutions could contribute to increasing network activity and further learning processes.

However, as these co-operational activities have not actually been comprehensive before along with the reluctance to let other value chain actors into their own process areas, the value proposition from this function remains still largely unused. As Näyhä and Pesonen (2014) point out, forest industry is seen as an adversarial business, leading the collaboration within and outside the industry to be somewhat neglected. In addition, the industry transition to the forest industry companies may turn out to be problematic. Even though the forest industry resembles the chemical industry, it does not work according to the same basic formula. For instance, significant differences in R&D intensity, specialization and different operational know-how are seen as a barrier when moving to a new industry. Wilson and Lee (2014) state that delivering high-value chemicals from biomass feedstocks demands improvements and innovations in catalysts and processes design. Therefore, reducing the knowledge gap between these industries with increasing knowledge diffusion continues to increase in significance in order to develop the required expertise, hence also setting requirements for the future policy variables.

Another material systemic function for triggering benign cycles in the pre-development phase, guidance of the search (Hekkert et al., 2011), encompasses also as some barriers to the development of the system. While Hellsmark et al. (2016) state that the crises of the Nordic pulp and paper industries and the declining demand for a part of their traditional products has been a promoting factor for the proactive look for more profitable new products and applications as well as the desirability of the value-added bioconversion of biomass due to the depletion of fossil fuels as well as the abundance, renewability and possible cost effective characteristics of lignocellulosic feedstock (Chen and He, 2012), the current blocking mechanisms affecting the system still require further attention. Especially unclear policy variables were seen as a hindering effect on the biochemical industry. According to Giurca and Späth (2017), the current bioeconomy-related policies at the EU level lack harmonization and are often symbolic while political intervention is seen as a fundamental tool for the shift towards a more sustainable economy, thus forming a somewhat adversarial situation regarding this function.

According to Purkus et al. (2018), it is important to consider the limited abilities of policy makers central steering knowledge, hence leaving room for decentralized experimentation combined with the use of dispersed knowledge. Since forecasting the outcomes from the processes of innovation and socio-technical changes is virtually impossible, a more feasible way for influencing the design of framework conditions could be formed from the policies which create collective expectations, thus reducing the uncertainty for investors and entrepreneurs. However, as mentioned earlier with regard to the F3, the current state of non-harmonized policies for the bio-based chemicals is considered to have a negative effect also on the company level, consequently weakening the resource mobilization function and further impacting the knowledge development. As Taylor et al. (2015) notice, few and unstable policies for biochemicals combined with a lack of market incentives are significant issues that need to be highlighted. Purkus et al. (2018) notice that the policy contexts characterized by high uncertainty and complexity require also flexibility for the policy adjustment as well as policy stability, therefore creating a central challenge for the transition policy design.

Moreover, in order to promote the system's further progression into the development phase, Hekkert et al. (2011) indicate the necessity to create policy measures to promote the entrepreneurial experimentation as this system function addresses the actual functionalities of the innovations regarding the first experiments and pilot plants. Svensson (2012) states that some necessary investments in traditional technologies might lead to lock-in effects, thus requiring an evaluation of both current and future investment opportunities with the same optimization model to enable the identification of investments. Furthermore, the dependence of biochemicals on the main product flows that determine their capacity must also be taken into consideration. Although the existing infrastructure and the complementary value chains enable further development and diffusion of the biochemical sector, Moshkelani et al. (2013) note that the integration of biorefinery units into a Kraft process places additional demands on existing processes, necessitating analysis to preserve the value of the current production assets.

With respect to the wood-based biochemicals, the competitive pressure does not only come from the incumbent fossil-based regime but the internal competition inside the forest industry may have a weakening effect on the further development of the system, too. As mentioned by the industry experts, the uncertainty about the future prospects will directly affect the corporate investment decisions, thus favoring lower-risk decisions in the incumbent technologies. When considering the pilot and demonstration plant activities, Frishammar et al., (2013) state that the spillovers from these activities may be advantageous for the recipient firms at the expense of the originators when the learning can be achieved at a fraction of total costs. Although beneficial for society at large, this may be discouraging for the commercial actors to take part in the development phase. Also, according to Näyhä and Pesonen (2014), the competitiveness of the forest industry and the tendency to copy competitor's business models, practices and products have hindered the willingness to innovate.

Furthermore, biochemicals face also competition from other innovation systems within the forest industry although the novel product areas might generate partly mutually supportive process synergies. Purkus et al. (2018) note that somewhat weak demand-pull from markets for innovative wood-applications call for direct demand-pull measures. Additionally, the long-term expectations about the market formation for the product novelties are required in order to further stimulate the entrepreneurial experimentation and upscale the technologies to develop economies of scale as well as learning effects.

Therefore, the wood-based biochemicals industry in Finland and other countries sharing a similar type of forest industry profile necessitate additional policy design. In order to complement conventional market and system failure arguments to take on board the requirements of the goal-oriented transformative change, Weber and Rohracher (2012) present additional multi-level perspective derived transformational system failures including directionality failure, demand articulation failure, policy coordination failure and reflexivity failure. Based on these as well as the functional strengths and weaknesses on the TIS, a mix of different policy instruments can be proposed. While the identification of specific policy instruments is out of the scope of this study, the purpose is to generate guidelines for the further development of the system.

When assessing from a broader perspective, the need for a strategic commitment to a path transition occurs. Purkus et al. (2018) state that creating stable collective expectations while also maintaining flexibility to adjust policy alignments to new information is fundamental. Since uncertain policy circumstances were stated as a significant weakness for the market actors, establishing a credible commitment on the level of strategies to enhance the reliability and stability for the policy framework may provide more incentives for the market actors to increase their participation in the TIS. Hellsmark, Mossberg, et al. (2016) address the importance of stable policy conditions in order to provide attractive profit opportunities. As these investments to novel technologies have long payback periods and are potentially made by industries with alternative investment opportunities, visibility at the strategic level is vital. Overall, the large-scale deployment of advanced biorefineries remains essential for the development of the entire wood-based biochemicals industry.

While striving for collective expectations among the system actors, the implementation of the strategies demands coherent policies such as technology-specific policies (Jacobsson and Bergek, 2011) as well as technology-specific direct demand-pull instruments and technology-neutral indirect demand-pull instruments (Purkus et al., 2018). When considering the long time horizons with the development of relevant technologies and industrial production capacity, Jacobsson and Bergek (2011) state that allowing associated industries to operate solely in accordance with the traditional market mechanisms is not sufficient enough, necessitating a parallel fostering of the new technologies with the existing ones. By utilizing the emerging momentum of more sustainable solutions (Velkavrh et al., 2015), R&D and demonstration support could incentivize system actors to gradual entrepreneurial experimentation, hence building the system and creating further legitimacy for the product novelties.

Furthermore, specific demand-pull measures are also needed in order to create niche markets as well as facilitate the destabilization of the incumbent fossil-based regimes. According to Purkus et al. (2018), these instruments are intended to pull innovative product novelties into markets while also serving as a selection environment for the fossil- and bio-based processes. This selection environment is perceived to operate more efficiently when pressure is applied on the options with undesirable characteristics instead of solely increasing the value of the selected options. For example, Kivimaa and Kern (2016) suggest 'creative destruction' policies constituting structural reforms in legislation, withdrawing support from selected technologies and balancing involvement of incumbents in policy advisory councils.

Additional technology-specific direct demand-pull instruments may also accommodate the penetration of the new technological innovations to markets. According to Jacobsson and Bergek (2011), technology portfolios encompass technologies that vary in stage of development, thus requiring more than technology neutral policy measures. The formation of early niches provides a habitat for the technologies to be further developed, thus complementing technology neutral policy frameworks with the integration towards the mass-markets. However, Hellsmark, Mossberg, et al. (2016) state that only few niche markets exist naturally for the advanced biorefinery products, hence necessitating more detailed policy incentives. Exemplary policy measures that were suggested by industry experts included green public procurement actions as well as increased certification schemes and labelling in order to create knowledge and further legitimize the bio-based chemicals among the end-users.

Purkus et al. (2018) also notify the relevancy of the adequate progression with the policy mix design. Demand-pull measures appear as appropriate measures for more mature technologies closer to commercial production while Hekkert and Negro (2009) suggest that early stage procedures are associated especially with guidance of the search as well as knowledge development and diffusion. Still, as the exact relations between the maturities of the technologies and the sequential importance of the system functions are somewhat ambiguous, this results in synchronized co-evolvement of the technology development and the system build-up. Overall, as Kivimaa and Kern (2016) adduce, expanding beyond the technology-push and demand-pull instruments and considering wider range of policy instruments promote the creation and development of niches while also destabilize the incumbent regimes. Hence, it remains essential to not only focus on the policy measures in a narrow sense but integrate them as a part of a more comprehensive transition strategy in order to create desirable conditions for the further development and diffusion of the wood-based biochemical sector.

7. Conclusions

The present study analyzed the development of the wood-based biochemical sector in Finland by examining the drivers and barriers affecting the progression of the system. For this purpose, the following research questions were addressed: (1) What are the components of the innovation system of the forest-based biochemicals sector in Finland? (2) What are the system weaknesses and strengths of the forest-based biochemical sector development in Finland? and (3) What could be key policies to enhance the further development and diffusion of innovations in the biochemical sector? The theoretical framework of this study relied on the innovation system approach presented by Markard and Truffer (2008) and multilevel framework by Geels (2002), aiming to provide a holistic view regarding the functions affecting the evolution of the sector.

Several systemic weaknesses and strengths were identified but specifically important functions hindering the further development of the system were the functions *knowledge diffusion through networks* and *guidance of the search.* These functions play a key role in the early stages of the system development, thus emphasizing the importance to address the problems associated with these functions as efficiently as possible with different policy methods. Furthermore, these particular weaknesses also revealed clear shortcomings in the current policy measures related to the biochemical sector, hence necessitating a call for action in order to improve the prerequisites for operations and on the other hand, requiring more research on the subject.

When considering applicable policy variables, wood-based biochemical products should be considered as a part of a larger entity, thus demanding progressive policy design on the whole biochemical sector. Moreover, although biochemicals appear as a very interesting product area from the forest industry's perspective, the share of wood-based biochemicals in total volumes is likely to be quite small due to the limited production capacity. In addition, the techno-economic feasibility of the current solutions causes problems for the present industrial-scale biochemical production, leading market players potentially investing in alternative, lower-risk options. Failures to address the system weaknesses negatively affecting the systemic functions may significantly deflate the interest of the market operators, thus leading to serious consequences regarding the development of the TIS.

As this study focused more on identifying the systemic weaknesses and strengths, proposing detailed policy variables was outside the scope of this study, Furthermore, considering the complexity of the industry with regard to many heterogenous pathways and value chains, introducing suitable policy variables still remains somewhat ambiguous. Therefore, as stated by Purkus et al. (2018), further research could be directed, for instance, to the interplay between the small-scale niche support and indirect demand-pull measures in order to support the TIS functions as well as the contributions of networks and public-private intermediaries.

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9. Appendix

Questionnaire

Changes in value chains

- How are the current value chains formed within the bio-based chemicals production?
- What kind of effects does the introduction of bio-based chemicals have on the current value chains and how would the possible new value chains be formed?

The conditions for new operations

- Are there bottlenecks in the current activities which will prevent the emergence or introduction of the new innovations considering bio-based chemicals?
- Do different industry participants (e.g. businesses, universities, political institutions) share the same expectations and visions when it comes to the progression of the industry?
- Does diffusion of new knowledge and know-how between industry participants appear and what could be the ways to increase knowledge between participants? (e.g. joint ventures, innovation co-operations)

Future outlook

- Does apparent interest appear for the bio-based chemicals within the downstream of the value chain?
- What kind of distribution of different bio-based chemicals would be realistic in the future and how large could the share of the bio-based chemicals be when considering the whole chemical industry? (time frame e.g. 2020, 2030, 2050)

Kysymykset

Arvoketjujen muutokset

- Kuinka tämänhetkiset arvo-/tuotantoketjut muodostuvat biopohjaisten kemikaalien tuotannossa?
- Millaisia vaikutuksia biopohjaisten kemikaalien käyttöönotolla on nykyisiin arvo-/tuotantoketjuihin sekä kuinka mahdolliset uudet ketjut muodostuisivat?

Uusien toimintojen edellytykset

- Ilmeneekö nykyisissä toiminnoissa pullonkauloja (esim. teknologian puute, asenneilmapiiri, tukien puute), jotka haittaavat uusien innovaatioiden syntymistä tai käyttöönottoa?
- Ovatko toimialan osapuolten (esim. yritykset, yliopistot, hallinnolliset organisaatiot ym.) odotukset ja visiot yhteneväisiä toimialan kehityksen suhteen?
- Esiintyykö uuden osaamisen ja tiedon kehittämistä sekä leviämistä toimialan osapuolten välillä ja kuinka tietoisuutta voidaan lisätä osapuolten välille (esim. innovointiyhteistyö, tuotteiden uusien ominaisuuksien viestintä)?

Tulevaisuuden näkymät

- Ilmeneekö tuotantoketjun eri vaiheiden asiakkaiden tahoilta selkeää kiinnostusta biopohjaisiin kemikaaleihin ja mitkä tekijät vaikuttavat niiden käyttöönottoon?
- Millä tavalla biopohjaisten kemikaalien tuotealueiden osuudet sekä kokonaisosuus kaikista kemikaaleista tulee kehittymään eri aikaväleillä (2020, 2030, 2050)?